Bioeconomic Model Approach for A Fluctuating Fish Stock: Bioeconomic Assessment of Harvest Strategies for the Pacific Whiting Fishery

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Abstract

Bioeconomic Model Approach for a Fluctuating Fish Stock: Bioeconomic Assessment of Harvest Strategies for the Pacific Whiting Fishery

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Pacific whiting (*Merluccius productus)* is one of the most commercially valuable fish species in the Pacific coast groundfish fishery. Although much research has been devoted to the fishery, several biological uncertainties still exist in the Pacific whiting fishery management. This is especially true for the extreme variability in annual recruitment which causes fluctuations in stock abundance, and it is the most well known biological uncertainty for this species. Furthermore, the same stock of Pacific whiting is harvested by multiple stakeholders in the US and Canada, who have diverse motivations in harvesting/processing involve stock management. This biological uncertainty and these multiple competing interests create a difficult and complex management structure for the Pacific whiting.

This study developed a stochastic bioeconomic model of the Pacific whiting fishery in order to examine various fishing strategies from both economic and biological viewpoints. The fisheries model includes a hockey-stick recruitment function, which generates occasional extremely large recruitment, and multiple competing fishing sectors. This study applied linear harvest strategies which close the fishery when estimated biomass falls below a stipulated minimum biomass

level, and set catch quotas as a fraction of the surplus of existing biomass minus the minimum biomass level (By – B_{min}). To accumulate information about the variability of results from each strategy we perform 1,000 50-year simulations and then summarize the results. These summaries include: average and variance of annual harvest, average and variance of biomass, and average and variance of 50-year Net Present Values (NPV) for the fishery. This study concluded the harvest strategy with lower minimum biomass (5% of unfished biomass)and low fraction (0.2) would be desirable for three reasons; 1) maximization of catch and NPV, 2) stochastic dominance and 3) biomass conservation.

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Introduction

All commercially valuable fish species fluctuate in abundance, which leads to unavoidable changes over time in catches. Variability in catches is one of most serious problems a fishery can face. Two general economic consequences of fluctuations in catch are identified (e.g., Hannesson 1993):

a) Because the market demand is price sensitive, fluctuating harvests will cause price fluctuations. This may stabilize or destabilize fishing revenue, depending upon whether price elasticity of demand exceeds in one absolute value.

b) For any given average harvest, harvesting/processing capacity must increase as harvest fluctuations increase in magnitude (variance). Unless equipment is transferable among fisheries, the annual capital expenses rises with increase fluctuations.

Given these consequences, there must be a relationship between net economic value of fishery and the extent to which the target species fluctuates in abundance; clearly the fishing industry would prefer less variability in catch. Furthermore, from a biological viewpoint, stability in fish abundance is desirable as it reduces the danger of extinction (Steinshamn, 1998).

Several studies have examined the mean and variance of harvest in fluctuating stocks. Gatto and Rinaldi (1976) examined this when recruitment is governed by the Beverton – Holt stock-recruitment function and the stock is managed by constant catch or constant escapement strategies. Murawski and Idoine (1986) modeled the Atlantic surfclam fishery using a stochastic recruitment model when management is based on a constant catch strategy. Both of these studies concluded that there is a trade-off between the mean and variance in harvest.

Steinshamn (1998) compared constant catch, constant effort and constant escapement strategies in terms of the mean and variance of harvest in a fluctuating stock as well as the size of the stock when the population dynamics are governed by a surplus production model with a random error in the population growth term. While these studies successfully identified the consequences of adopting alternative harvest strategies for fluctuating stocks conceptually, they used highly simplified models instead of the types of models on which actual management decisions are based.

Pacific whiting (*Merluccius productus)*, also known as Pacific hake, has exhibited historical fluctuations in abundance. The fishery for Pacific whiting produces the greatest harvest of any fisheries off the U.S. and Canadian Pacific coasts. The life history and biology of Pacific whiting has been well-studied (Bailey *et al.,* 1982; Fancies *et al.,* 1983; Swartzman *et al.*, 1983; 1987; Dorn and Methot 1990 and Methot and Dorn 1995; Done *et al.,* 1999; Helser *et al.,* 2002). However, two major biological uncertainties still exist: (a) the causes of the extreme variability in recruitment, and (b) the reasons why changes in annual migration patterns occur. Both of these uncertainties have major impacts on the fisheries for Pacific whiting. The most important of these is recruitment variability; recruitment of Pacific whiting can be extremely large and totally independent of the size of the spawning stock. The presence or absence of large year-classes leads to substantial changes over time in abundance, and hence challenges for management.

The fisheries for Pacific whiting are complicated, which compounds the problem of fisheries management for this species. The same stock is harvested by U.S. and Canadian fisheries, creating the need for a multi-national management. Within the U.S. fishery, there are multiple stakeholders including at-sea processors, on-shore processors, and tribal fishers. The Canadian fishery involves on-shore processors and joint ventures with Russia and other Eastern Europe countries.

The fishery management system consists of the interaction between fish and humans, and not just fish population dynamics. The fishery bioeconomic model approach, which combines fish population dynamics and the economic components of the fishery system, is developed to express this interaction through harvest activities. The responses of the fish stock to human activities (i.e. fishing effort, gear selection) and the economic consequences of specific harvest strategies can be examined by including the management objectives in the models on which management decisions are based. In a previous study, Hanneson (1993) applied the fishery bioeconomic model approach to identify economically optimal harvest strategies for the fishery for Arcto–Norwegian cod, a species that exhibits considerable fluctuations in stock size. However, there are only a few studies have been done for the application of bioeconomic approach in fluctuating fish stock (e.g., Steinshamn 1998).

This study has two objectives:

1) construction of a stochastic bioeconomic model for the Pacific whiting fishery which captures the possibility of occasional extremely large recruitment events; and

2) examination of the trade –off between average and variance, the economic and biological consequences of different harvest strategies by means of simulation.

Chapter 1 describes the biology of Pacific whiting and the historical development of the fisheries for Pacific whiting. Chapter 2 overviews uncertainty and risk in the fishery management context and Chapter 3 develops the stochastic bioeconomic model for the Pacific whiting fishery. Chapter 4 describes the harvest strategies considered and the set of performance indicators used to summarize the consequences of each harvest strategy. Chapter 5 summarizes the result of the simulations and discusses the ramifications of variability of yield and economic performance.

Chapter 1: Overview of the Pacific whiting fishery

1.1 Biology of Pacific whiting

Pacific hake (*Meluccius productus*) is a cod-like species that inhabits the near shore ocean off the west coast of North America. Several genetically distinguishable stocks of Pacific whiting are found within the management area of the Pacific Fishery Management Council (PFMC)[1]. The stock that is the focus for this study is the most abundant and is distributed coast-wide. It can be distinguished from the inshore stocks which are found in the major inlets of the North Pacific Ocean (e.g. Strait of Georgia, Puget Sound, and the Gulf of California) by their larger body size, substantial annual migrations, and occasionally very large year-classes (Dorn *el al*. 1999). The fishery for Pacific whiting targets primarily the coastal stock. The inshore stocks are not considered further in this study.

Stock assessments of the Pacific whiting are conducted every three years, the last being in 2001. The biomass (ages 3 and older) of Pacific whiting (1972-2001) has varied from 5.737 millions tons in 1987 to 0.725 million tons in 2001 (Figure 1.1). The biomass was highest in 1987 due to the impact of the strong 1980 and 1984 year-classes. Since 1987, the biomass has been dropping due to fishing pressure and the lack of any very strong year-classes. The 2001 biomass is the lowest since 1972 and resulted in the stock being declared overfished under the Sustainable Fisheries Act by the National Marine Fisheries Service.

[1] The PMFC divides its management area into five regions: Vancouver, Columbia , Eureka, Monterey, and Conception.

The most remarkable biological characteristic of Pacific whiting is that there are occasionally extremely large recruitments, which are to be unrelated to the size of the spawning biomass (see Chapter 3 for further details).

Pacific whiting are found from Baja California, Mexico to Vancouver Island, Canada and are migratory. The largest and oldest individuals of the population are found in the northernmost end of the range and this end of the range also has the highest proportion of sexually mature females (Sylvia and Enrizuez 1994; Alheit and Pitcher (*editors*) 1995; Helser *et al.,* 2002). Spawning occurs off central and southern California during January and February, after which the animals migrate north. In autumn, adult Pacific whiting make a return migration from their summer feeding grounds to their winter spawning grounds (Francis 1983).

The migration patterns are sex- and size-specific. For example, the larger individuals appear off Oregon and Washington from the south in April, and the smaller individuals arrive later. Schools of large Pacific whiting appear off Vancouver Island, British Columbia, Canada in late May. Males, which are smaller than females, arrive later in Canadian waters than females, and migrate south earlier. One result of this is that females contribute 60-80% of the catch off Canada. Furthermore, weight-at-age in the catch is higher in Canada than in the U.S. (Figure 1.2). Pacific whiting, in common with most hakes of the genus *Meluccius*, are cannabilistic. The geographic separation of juveniles and adults during the annual migration therefore reduces the impact of cannibalism[2].

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[2] Silver hake in the East coast of the U.S has a significant impact of cannibalism for juveniles. Helser (1998) built a population dynamics model of silver hake which included density effect for juveniles (e.g., density dependent mortality).

The timing of the southward migration and the environmental factors that influence it are currently not well known (Methot and Dorn 1995). From 1994-99, spawning and juvenile settlement tended to spread northward due to El Nino ocean conditions (Helser *et al*. 2002). This led to a reduction in the size of the adult stock off the U.S. and a consequential increase off Canada. However, this trend reversed in 2000, when the stock did not extend much beyond the Oregon-Washington border. This resulted in a very small proportion of the stock reaching Canada in 2000 and 2001. (Buckley and Livingston 1997).

1.2 Management of the Pacific whiting fishery off the US West coast

The U.S. West Coast groundfish fishery is managed by the Pacific Fishery Management Council (PFMC), which is one of the eight Regional Fishery Management Councils established under the Magnuson-Stevens Fishery Conservation and Management Act of 1976 and the Sustainable Fisheries Act of 1996. The PFMC has developed Fishery Management Plans for species within the U.S. Exclusive Economic Zone (EEZ) off the coasts of Washington, Oregon and California (PFMC, 2001). The harvest of Pacific whiting is the largest of any groundfish species managed by the PFMC (Table 1.1).

Large-scale commercial fishing for Pacific whiting occurs from northern California to Vancouver Island, British Columbia during the spring and summer months. The annual harvest averaged 156,482 metric tons and 51,295 metric tons for the U.S. and Canada respectively between 1966-2001 (Figure 1.3). The trend in the catches by the two countries is highly correlated after 1984 although this is likely to be due to the introduction of a stock wide quota based on an Acceptable Biological Catch since then.

1.3 Historical development of the Pacific whiting fishery

The fishery for Pacific whiting operating within U.S. waters was small before 1966 and most of the harvest was delivered to reduction plants for animal feed (Nelson 1985). Sectors operating in the Pacific whiting fishery on the U.S. West Coast have changed rapidly since 1966 (Figure 1.4). In general terms, fishing by foreign vessels ended with passage of the Magnusson-Stevens Act in 1976 and the declaration of the 200NM EEZ soon thereafter. Fishing by foreign vessels was replaced by joint-ventures between US companies and foreign entities, initially the Soviet Union and then later companies in Poland, Japan, the former Soviet Union, the Republic of Korea and the People's Republic of China (Methot and Dorn 1995; Dorn *at el.,* 1999) and this was in turn replaced by fishing by vessels owned by U.S. companies. Joint-ventures with Russian and other eastern European-based companies still (2002) occur off Canada.

Pacific whiting products are primarily frozen blocks of fillets, headed and gutted fish, surimi, and fishmeal (Sylvia and Enrizuez, 1994). Processing of Pacific whiting into surimi commenced in 1989 when Japanese motherships began to produce surimi using then new processing technologies. The potential markets for Pacific whiting increased after 1989 because of the high demand for surimi in far east Asia and this led to an increase in the capacity of the U.S. fleet and the phasing-out of joint ventures in U.S. waters.

Table 1.1. PFMC Acceptable Biological Catch (ABC) and Optimum Yield (OY) recommendations for 2001 for Washington, Oregon and California (from PFMC, 2001b). Units are metric tons.

	Total ABC 2001	**Final Recommended Optimum Yield(OY) for 2001**	**OY for 2000**	**Change from 2000**
Pacific whiting	**190,400**	**190,400** [3]	**232,000**	**-18%**
Shortbelly rockfish	13,900	13,900	13,900	NC
Sablefish	7,661	6,895	6,895	-13%
Widow rockfish	3,727	2,300	4,333	-47%
Yellowtail rockfish	3,146	3,146	3,539	-11%
Cilipepper rockfish	2,700	2,000	2,000	NC
Lingcod	1,119	611	378	62%

[3] The combined ABC for the U.S and Canada is 238,000mt. The U.S. OY is 80% of this (190,400 MT).

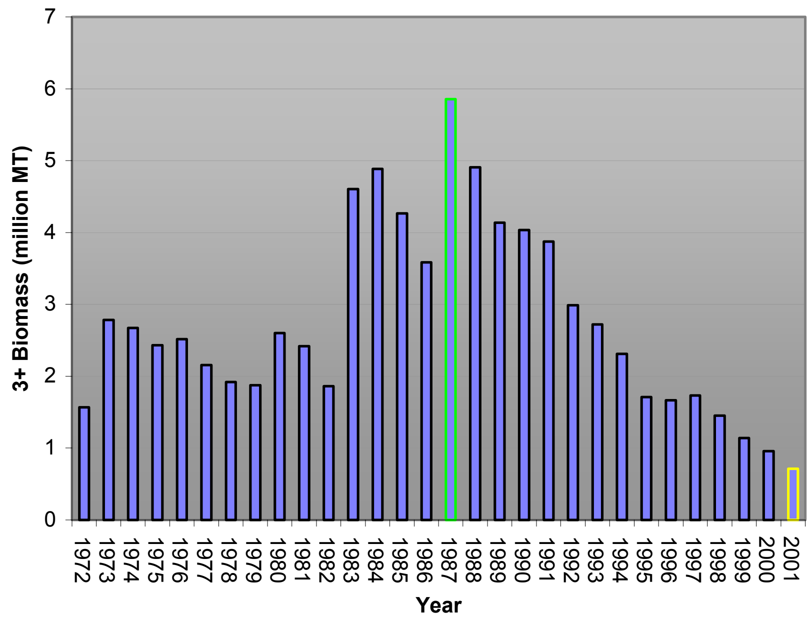

Figure 2.1. 3+ biomass time-trajectory for Pacific whiting. The results in this figure are based on the maximum likelihood estimates from the assessment conducted by Helser *et al*. (2002).

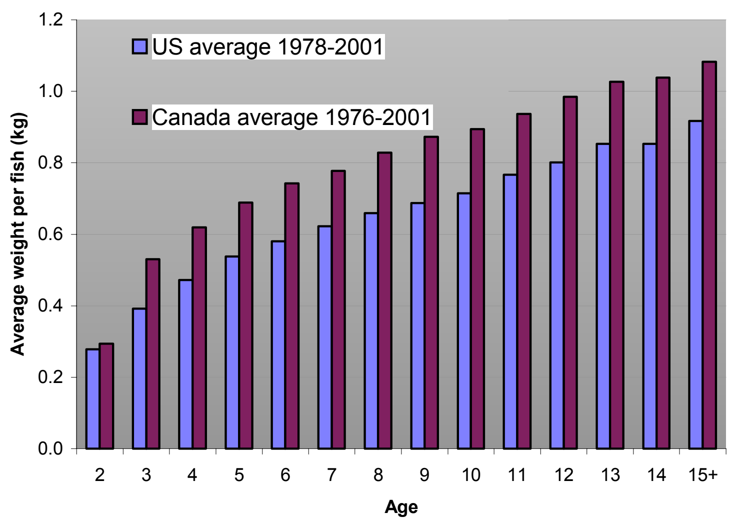

Figure 1.2. Average weight-at-age of individual fish in the catch (Source: Helser *et al.,* 2002).

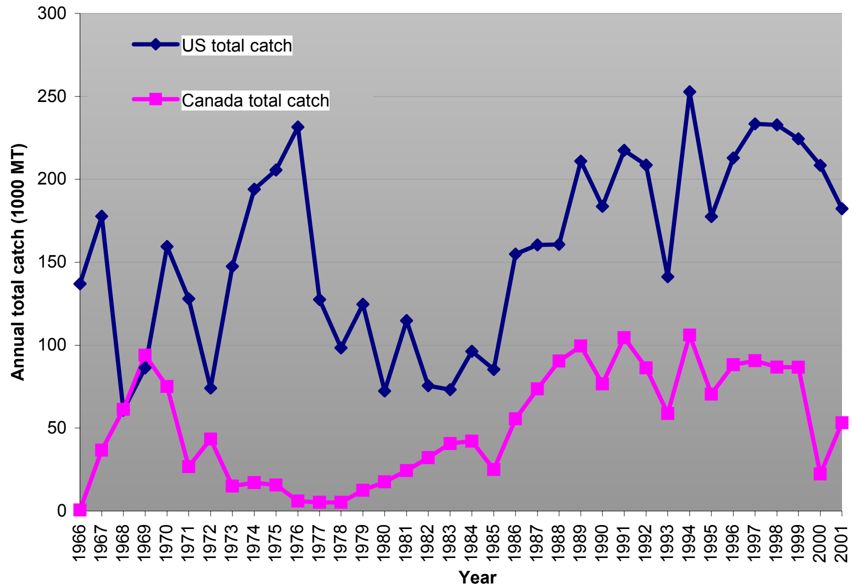

Figure 1.3. Annual landings of Pacific whiting by the U.S. and Canada (Source: Helser *et al.,* 2002).

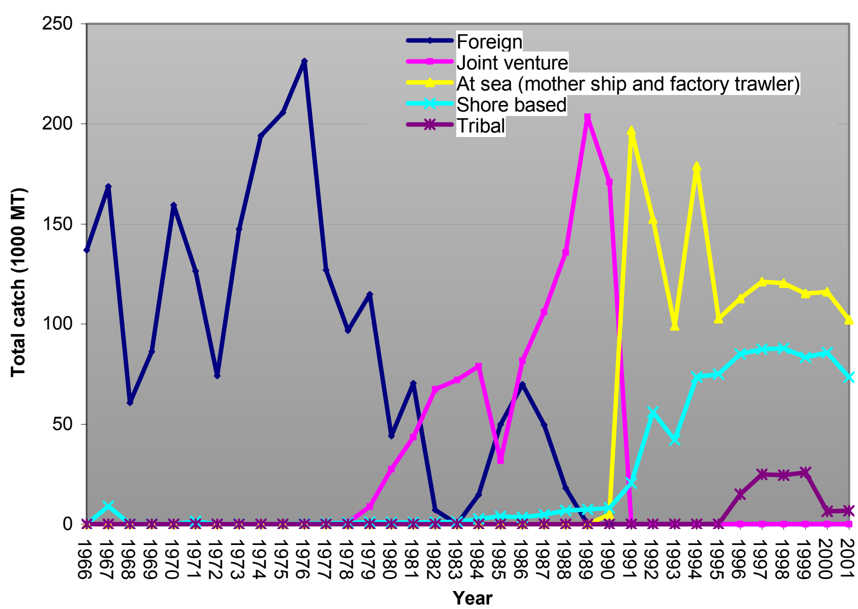

Figure 1.4. Annual catches of Pacific whiting off the U.S. by fishery sector (Source: Helser *et al.,* 2002).

Chapter 2: Uncertainty and risk in the fishery system

Our cognitive system introduces error or bias into our judgments, as a result of uncertainties (Morgan and Henrion 1990). Risk is defined as the probability of something bad happening. The past decade has seen a growing recognition of uncertainty and risk in fishery management owing, in part, to the collapse of many fishery resources around the world. One result of this is the literature focusing on uncertainties in fishery management (*e.g.,* Gordon and Munro (ed.s) 1996; and Berkson, Kine and Orth (ed.s) 2002).

This chapter first provides an overview of uncertainty and risk in the fishery system, and then introduces the types of uncertainties that will be included in the bioeconomic model that will form the basis for this study.

2.1 Uncertainty and the fishery system

Economists usually focus on the effects of uncertainty and risk in the context of microeconomics: if the future could be predicted perfectly, without information cost, firms could accurately anticipate the opportunities that would lead to economic return (Ruffin and Gregory 1997). Uncertainties, however, surround industries and we cannot predict the future perfectly. Therefore, firms make decisions on activities that involve risk and hence the possible loss of investment and returns (profits). Risk, therefore, is inherently analyzed in conjunction with probabilities of various outcomes. Like other industries, fishing industries face many uncertainties and risks, but they also face unanticipated changes fish stocks and fishing regulations.

Charles (2001) describes the fishery system as the combination of: direct fishing, post–harvest activities, and the surrounding environments such as ecosystems, fishing communities, and biophysical and socio-economic components. This complex system is associated with a variety of sources of uncertainty; for example, the status of stocks, environmental conditions, and price/demand of harvest in the market. These types of uncertainties are also present in other renewable natural resource contexts such as agriculture, dairy farming and forestry. The genesis of uncertainty in the fishery system is, however, different from those for other renewable natural resources. Hilborn (2002) quoted John Shepherd as saying "counting fish is like counting trees, except that they are invisible and they keep moving." Most uncertainties in fishery systems are caused by the uncountable nature of fish even given the stock assessment process. The largely unpredictable nature of fish also leads to uncertainties related to biological processes. For example, it is possible to determine (by observation) the actual annual reproductive rate for a female cow, or to know that the number of trees would not double suddenly from one year to the next. However, it is impossible, even retrospectively, to determine how many eggs one fish spawns annually or how many juveniles survived from the egg stage to the larval stage. All that is possible in the fishery system is to estimate the magnitude of these processes using imperfect information, which leads to considerable estimation uncertainties.

Hilborn *et al* (1993) describe how uncertainty and risk are linked in fishery management when they state that uncertainty and risk from the viewpoint of fishery managers consists of "two critical aspects of the stock assessments process, the uncertainty of stock assessment ("statistical inadequacies") and the risk in decision making". Uncertainties in stock assessments are always a major concern for fishery managers; they *must* make decisions, even if enormous uncertainty exists.

While fishery managers focus on risks associated with loss of catch or fish stock collapse, the fishery industry is concerned with the risk associated with loss of capital or the failure of investment or return. One frequent characteristic of fishing industries is the irreversibility of investment. Once an investment is made in a fishery (e.g. building a vessel or a processing plant), it cannot typically be transferred to another industry. Enormous uncertainties make investment in the fishing industry riskier than in many other industries. In most cases, government subsidies play a role in neutralizing fishing industry risk, thus alleviating the enormous uncertainties and the irreversibility of investment.

In the Pacific whiting fisheries, an occasional extremely large recruitment causes fluctuations in the stock and the catch. In other words, occurrences of extremely large recruitments lead to additional uncertainties (e.g., Will catches be increased by good recruitment? Will any increased catches remain high? etc.). For the fishing industry, therefore, highly variable recruitment complicates the decisions to invest in expanded harvest or processing capacity. In addition, fishery managers will repeatedly face decisions to alter harvest quotas by significant amounts because of these variable recruitments (*e.g.,* difficulty in setting biological reference points).

2.2 Uncertainties surrounding the fishery system

Several types of uncertainties impact fishery assessments and systems (Hilborn and Mangel 1997; Haddon 2001; Punt 2002). These uncertainties include:

1) model uncertainty – associated with the choice of particular functional forms for components of the model used to represent the system;
2) process uncertainty – fluctuations in the value of a quantity about its deterministic mean – this source of uncertainty reflects unmodelled components of the entire fishery system (Francis and Shotton, 1997, Charles, 2001) ;
3) parameter uncertainty – associated with the precision of parameter estimates

given a model and the data used when fitting it; and

4) observation uncertainty – measurement error associated with the data used to determine the values for the parameters of a model.

Since these uncertainties are part of the fishery system, any models of the fishery system need to consider and include them. The bioeconomic model of this study includes two types of uncertainties:

1) The "process uncertainty" and the "parameter uncertainty" associated with the stock-recruitment (SR) relationship. This study is based on only one stock-recruitment relationship (the "Hockey stick" stock-recruitment relationship) so "model uncertainty" is ignored. "Process uncertainty" about the SR model leads to (occasionally large) fluctuations, and this is the main focus of this study. "Parameter uncertainty" is reflected by generating the parameters of the Hockey Stick SR relationship from a joint distribution based on the fit of an assessment model to data for Pacific whiting.

2) Observation uncertainty associated with assessing the Pacific whiting biomass. The TAC is based on an estimate of population size that is subject to temporally correlated error, so that if the estimate of current biomass overestimates the true abundance in one year, this is also likely to happen the next year.

The following chapters outline the detailed specifications of how these uncertainties are implemented in the bioeconomic model of the Pacific whiting fishery.

Chapter 3: Pacific whiting fisheries bioeconomic model

In this chapter, a fishery system (or bioeconomic) model that includes uncertainty and socioeconomic factors is developed for Pacific whiting. A model of the basic population dynamics is outlined first. Next, a model of the relationship between recruitment and spawning stock biomass that takes account of the uncertain nature of Pacific whiting reproduction is described. This is followed by a description of an economic model that includes two nations and multiple sectors. The final section of this chapter describes how these three models are integrated in a simulation context.

3.1 Population dynamics model

An age-structured population dynamics model, based on that of Helser *et al* (2002), was developed for the Pacific whiting to act as the biological component of the bioeconomic model. The use of an age-structured population dynamics model, as opposed to an age-aggregated population dynamics model, is justified for two reasons:

(a) Pacific whiting exhibit an age-specific migration pattern (Francis *et al* 1982; Swartzman *et al* 1983; Helser *at al* 2002). Older fish tend to migrate northward towards Canadian waters, while young fish tend to stay to the south, in US waters, resulting in the Canadian and US fisheries targeting different ranges of age-classes; i.e. the Canadian fishery harvests older Pacific whiting than the US fishery (see Chapter 1). In other words, these two fisheries have different fishery selectivity patterns. The age-structured model is capable of capturing the effects of these two fisheries adequately.

(b) The main objective of the bioeconomic model is to examine the economic consequences of fluctuations in the Pacific whiting stock caused by recruitment variability. An age-structured model is necessary in order to include recruitment explicitly.

The age-structured population dynamics model includes three basic components: recruitment, mortality and individual fish growth (Quinn and Deriso 1999). Recruitment will be discussed in relation to spawning stock biomass in the next section. This section describes the time-series dynamics of Pacific whiting cohorts which depends on instantaneous fishing and natural mortality rates, as well as the change in biomass that results from the impact of individual fish growth.

The change in the size of a cohort from one year to the next is modeled using the exponential decline equation:

$$N_{i+1,y+1} = \begin{cases} N_{i,y} e^{-Z_{i,y}} & \text{if } i < 14 \\ N_{14,y} e^{-Z_{14,y}} + N_{15,y} e^{-Z_{15,y}} & \text{if } i = 14 \end{cases} \qquad (3.1.1)$$

$$Z_{i,y} = F_{i,y}^{\text{Total}} + NM_i \qquad (3.1.2)$$

where $N_{i,y}$ is number of fish of age *i* at the start of year *y*,

$Z_{i,y}$ is total instantaneous mortality rate on fish of age *i* during year *y*,

$F_{i,y}^{\text{Total}}$ is total instantaneous fishing mortality rate on fish of age *i* during year *y*, and

NM_i is instantaneous rate of natural mortality on fish of age *i* (assumed to be independent of age and equal to 0.23yr^{-1} – Helser *et al.*, 2002).

The exponential decline model (Equation 3.1.1) assumes that fishing and natural mortality occur continuously throughout the year. This assumption seems valid *a priori*. In contrast, Pacific whiting fishing seasons are limited to specific time periods (April to October), creating discrete instances of fishing mortality. However, the impact of ignoring this is likely to be relatively minor and continuous fishing mortality is a more plausible assumption than the alternative of a pulse fishery since fishing occurs over a 7-month period. Recruitment is modeled as occurring at age 2 (see next section for more details) and all fish 15 years and older are pooled into a 15 year plus-group. The population dynamics model therefore considers 14 cohorts (ages 2 to 15).

Total instantaneous fishing mortality is defined in terms of fishing selectivity and fully-selected fishing mortality. Separate selectivity parameters and fully-selected fishing mortalities are calculated for the Canadian and US fisheries. Like Helser *et al* (2002), who allow fishing selectivity to change over time, the study assumes that future selectivity will equal the average fishing selectivity estimated for over 1992-2001:

$$F_{i,y}^{\text{Total}} = s_i^{\text{Canada}} f_y^{\text{Canada}} + s_i^{\text{US}} f_y^{\text{US}} \tag{3.1.3}$$

where $s_i^{\text{Canada}}, s_i^{\text{US}}$: fishery selectivity for age *i* (Canada / US), and

$f_y^{\text{Canada}}, f_y^{\text{US}}$: fully-selected fishing mortality during year *y* (Canada / US).

The model keeps track of the 3+ biomass (B_y) and the spawning stock biomass (SSB_y). The weight of a fish of age *i*, w_i, is assumed to be time-invariant and equal to the weights-at-age for 2001 in Helser *et al* (2002):

$$B_y = \sum_{i=3}^{15} N_{i,y} w_i \qquad (3.1.4a)$$

$$SSB_y = \sum_{i=2}^{15} N_{i,y} \cdot w_i \cdot m_i \cdot \iota_i \qquad (3.1.4b)$$

where m_i : proportion of females of age *i* that are mature, and

ι_i : multiplier for proportion of the female of age *i* in population.

The catch (c_y^l) in weight by nation *l* during year *y*, c_y^l , is given by the equation:

$$c_y^l = \sum_{i=2}^{15} w_i \, N_{i,y} \frac{F_{i,y}^l}{Z_{i,y}} [1 - \exp(-Z_{i,y})] \qquad (3.1.5)$$

3.2 Spawning stock and recruitment model

The abundance of a fish biomass can fluctuate substantially over time. In most cases, variability of annual recruitment[4] is the main cause of fluctuations in stock size (Cushing 1977; Quinn and Deriso 1999). As is the case for many other fish species, recruitment variability (occasional extremely large recruitments) is the major reason for fluctuations in the biomass of the stock of Pacific whiting (Helser *et al* 2002). This variability is caused by changes in spawning stock biomass (SSB), environmental variations, or a combination of both of these factors (Haddon 2001). Although many fisheries scientists have attempted to identify empirical relationships between recruitment and these factors, the nature of fisheries data (*i.e.,* short noisy time-series), makes this difficult (Hilborn and Walters 1992).

Previous Pacific whiting bioeconomic studies have been based either on age-aggregated surplus production models or on age-structured models with

[4] The age-at-recruitment is sometimes taken to be age 0. In this study, the recruitment is defined to be the number of fish at the time of first entry to the fishery (*e.g.,* the youngest age that is vulnerable to the fishery)

constant recruitment (Conrad 1990; Sylvia and Enriquez 1994; Larkin and Sylvia 1999). Neither of these approaches requires an explicit stock-recruitment (SR) model that captures the relationship between the size of the spawning stock biomass (the parental stock) and recruitment. Conrad (1990) used an age-aggregated surplus production model in his bioeconomic analysis of the Pacific whiting fishery. Since a surplus production model aggregates both individual fish growth and recruitment, it does not explicitly quantify the relationship between spawning stock biomass and recruitment[5]. The use of an age-aggregated surplus production model in bioeconomic analyses has the advantage that the calculations can be conducted analytically. For this reason, fisheries economists often prefer to assume that the population dynamics are governed by an age-aggregated surplus production model rather than by an age-structured model. While analytical solution methods may be used when the population dynamics are approximated by an age-aggregated model, assuming that the population dynamics are governed by an age-structured model usually requires numerical methods to achieve solutions because of complexity. Sylvia and Enriquez (1994) used an age-structured model under the assumption that the recruitment of Pacific whiting is independent of the size of the spawning stock biomass. While these two studies have successfully analyzed the Pacific whiting fishery under these specific assumptions, they ignored variability and its implications. The relationship between spawning stock biomass and recruitment is an essential element of the bioeconomic model of this study, because this study focuses on the implications of the fluctuations in the stock caused by variation in recruitment.

Models describing processes of interest are called “process models” (Hilborn and Mangel 1997). The stock-recruitment model is therefore a “process model” that describes the impact of spawning stock biomass on recruitment. In

[5] Surplus production models aggregate the impacts of growth of individual fish and recruitment, and ignore age-structure dynamics.

principal, a SR model for any fishery can be based on historical data. However, a SR model has yet to be introduced for the Pacific whiting.

This section first introduces a parameterized SR model, the Hockey Stick model (HS model), then quantifies the extent of process uncertainty about the relationship between spawning stock biomass and recruitment, as well as the uncertainty about the values for the parameters of this SR model.

Spawning stock and recruitment information for Pacific whiting

Figure 3.1 shows the maximum likelihood estimates of spawning stock biomass and recruitment for Pacific whiting for the years 1972-2001 (Helser *et al* 2002). Recruitment is defined as the abundance of Pacific whiting aged 2 years and spawning stock biomass is defined as the biomass of mature females (see Equation 3.1.4b). Therefore, there is a two year difference between when spawning occurs and when recruitment takes place (*i.e.,* the 1999 year-class recruits in 2001). The two extremely large recruitments (the 1980 and 1984 year-classes) make identifying the underlying nature of the stock-recruitment relationship virtually impossible. Furthermore, the recruitment in 2001 (the 1999 year-class) was relatively large despite a low spawning stock biomass in 1999. High recruitment at low spawning stock biomass impacts the resilience of the population (i.e. the slope of the stock-recruitment relationship close to the origin) markedly. In practical fisheries management, the resilience of the stock and the recovery time for overexploited species are usually calculated from the marginal increase of expected recruitment at low spawning stock biomass (Barrowman and Myers 2000).

Extreme stock-recruitment points (such as those for 1982, 1986 and 2001 in Figure 3.1) are often ascribed to favorable environmental conditions (*e.g.,* water temperature, food availability) during the egg and larval stage. For instance, in the case of tiger prawns (*Penaeus esculentus*) off Western Australia, Penn and Caputi

(1985) suggested that extremely high recruitment is associated with a change in rainfall during January and February. In the case of the West Coast groundfish fishery, Clark and Hare (2002) identified a correlation between the El Nino phenomenon and the recruitment pattern of Pacific halibut (*Hippoglossus stenolepis*). For Pacific whiting, however, the environmental determinants for extreme recruitment events has yet to be postulated let alone identified.

Overview of the Hockey Stick stock-recruitment model

The version of the hockey stick model considered in this study is a reparameterized version of that developed by Barrowman and Myers (2000). The hockey stick model consists of a linear increase in recruitment from the origin to a threshold biomass level, $S*$, after which recruitment is constant at a level of $R*$.

$$R_{y+2} = \begin{cases} \alpha S_y = R^* \dfrac{S_y}{S^*} & \text{if } S_y < S^* \\ \alpha S^* = R^* & \text{if } S_y > S^* \end{cases} \tag{3.2.1}$$

where S_y is spawning stock biomass at the start year y
R^* is recruitment when the spaniwng stock biomass exceeds S^*
α is rate of incerease in recruitment at low spawning stock biomass $\dfrac{R^*}{S^*}$

The hockey stick model therefore assumes that recruitment is proportional to spawning stock biomass when spawning stock biomass is less than the threshold spawning stock biomass. However, if the spawning stock biomass is above the threshold level, recruitment is independent of spawning stock biomass, presumably because of the impact of density-dependent mechanisms such as cannibalism, epidemic disease, and food availability.

Reason for using of the hockey stick model for Pacific whiting

There are two reasons to use the hockey stick model for Pacific whiting.

a) Robustness of model shape. Hilborn and Walters (1992) state that harvest strategies should be robust to unpredictable or uncontrolled biological fluctuations to avoid unnecessary modifications to management plans. The problem associated with fitting conventional (Beverton-Holt or Ricker) stock-recruitment relationships to data for Pacific whiting (as illustrated later) is lack of robustness of model shape. Specifically, extreme recruitment events affect the resilience (shape) of conventional stock-recruitment models substantially. However, the shape of the hockey stick model is robust to this.

b) The hockey stick model is somewhat more consistent with the approach used to estimate annual recruitment for Pacific whiting than the other models. This is because the assessment approach assumes that recruitment is independent of spawning stock biomass (Helser *et al*, 2002); annual recruitment being distributed log-normally about a mean recruitment value. The hockey stick model makes this same assumption if the spawning stock biomass is larger than the threshold level.

Fitting the stock-recruitment relationships

Recruitment of Pacific whiting is characterized by infrequent, very large, year-classes (see Figure 3.1). The distribution of recruitment about the deterministic component of the stock-recruitment relationship is usually assumed to be lognormal because the alternative of a normal distribution implies that negative recruitments are plausible (Barrowman and Myers, 2000; Haddon, 2001).

Following Barrowman and Myers (2000) and assuming that recruitment is log-normally distributed about the model-estimates, the relationship between spawning stock biomass and recruitment is given by:

$$R_y = \alpha\, f_\phi(S_y) e^{\varepsilon_y} \qquad (3.2.2)$$

where $f_\phi(S_y)$ denotes a function of spawning biomass, *e.g.,*:

$$R_y = \alpha\, f_\phi(S_i) \cdot e^{\varepsilon_y} = \begin{cases} \frac{\alpha S_y}{\beta + S_y} e^{\varepsilon_y} & \text{Beverton-Holt} \\ \alpha\, S_y\, e^{-\beta S_y}\, e^{\varepsilon_y} & \text{Ricker} \end{cases} \qquad (3.2.3)$$

and e^{ε_y} denotes lognormal process error. Taking the natural logarithm of Equation (3.2.2), gives:

$$\ln R_y = \ln \alpha + \ln f_\phi(S_y) + \varepsilon_y \qquad (3.2.4)$$

The error term (ε_y) in Equation (3.2.2) is a Gaussian random variable (identically and independent normally distributed), given the hypothesis that recruitment is lognormally distributed about its expected value. This leads to the following likelihood function:

$$L = \prod_{y=1}^{n} \frac{1}{R_y \sqrt{2\pi}\sigma_R} e^{\left[\frac{-(\ln R_y - \log f_\phi(S_y))^2}{2\sigma_R^2}\right]} \qquad (3.2.5)$$

where σ_R^2 is the process-error variance. Instead of maximizing the likelihood function, the parameters of the stock-recruitment relationship are determined by minimizing the negative of the logarithm of the likelihood function:

$$-\ln L = n\ln\sqrt{2\pi} + n\ln\sigma_R + \sum_{y=1}^{n}\ln Ry + \sum_{1}^{n}\frac{\left\{\log R_i - \log f_\phi(S_i)\right\}^2}{2\sigma_R} \qquad (3.2.6)$$

The two parameters of the hockey stick model, S^* and R^*, are estimated by minimizing Equation 3.2.6 using a numerical procedure (Sequential Quadratic Programming in MATLAB).

Result of fitting the Hockey Stick model

The maximum likelihood estimates for annual recruitment are shown along with the fit of the hockey stick model in Figure 3.2. The residuals about this fit are shown in Figure 3.3 while Figure 3.4 shows a contour plot of the negative log-likelihood as a function of S^* and R^*. The symbol “A” in Figure 3.3 denotes the minimum region of the negative log-likelihood function.

Likelihood profiles for S^* and R^* are shown in Figures 3.5(a) and 3.5(b). The lowest negative log-likelihoods in Figure 3.5 (a) and 3.5 (b) correspond to region “A” in Figure 3.4. The value of R^* is relatively well-determined by the data. However, this is not the case for S^*. In fact, there is not even a unique minimum to the negative log-likelihood function - all points satisfying ($R^* = 0.706$; $0 < S^* < 0.561$) correspond the minimum of the negative of the log-likelihood function (36.932). The inability to place a lower bound (other than zero) on S^* occurs because the data are insufficient to define the slope of the stock-recruitment relationship close to the origin. To avoid this problem, the value of S^* is constrained to lie within the lower bound range of observed spawning biomasses.

Comparison with other stock-recruitment models

Figure 3.6 shows the fits of three stock-recruitment models (hockey-stick, Beverton-Holt and Ricker – see Equation 3.2.3) to the maximum posterior density estimates of recruitment and spawning stock biomass).

The Beverton-Holt and Hockey Stick models provide almost identical fits to the data (Figure 3.6; Table 3.1) while the fit of the Ricker model is slightly (but not significantly) poorer. It is noteworthy that recruitment expected at low spawning biomass is much higher for the Beverton-Holt than for the Hockey Stick and Ricker models (Figure 3.6).

Figure 3.7 illustrates the sensitivity of the fits of the Beverton-Holt (BH) and hockey stick (HS) models to excluding the data for 2001. The recruitment during 2001 was estimated to be high (~3 billion) even though the spawning stock biomass in 2001 was the lowest in the time-series. While the predictions of the BH model are highly sensitive to whether the data point for 2001 is included in the analysis or not (particularly in terms of its predictions of recruitment at high levels of spawning biomass), this is not the case for the hockey stick model. This robustness to extreme data points is one of the reasons for using the hockey stick model (see Section 3.2.3).

Allowing for parameter uncertainty

The assessment of Pacific whiting is based on a Bayesian approach which involves applying the Markov Chain Monte Carlo (MCMC) algorithm to sample large numbers of parameter vectors from the joint posterior distribution for the parameters (Helser *et al* 2002). For recruitment, this process involves updating prior distributions for mean recruitment and the annual deviations in recruitment about that mean using data on catch-at-age from the commercial fisheries and survey data. The MCMC algorithm can also be used to generate spawning biomass and recruitment data sets. In order to reflect the variability arising from the Bayesian assessment in terms of the values for the parameters of the hockey stick model (parameter uncertainty), this model was fitted to 1,000 stock-recruitment data sets generated from the posterior distribution.

Variability in the values for the parameters of the Hockey Stick model

Figure 3.8 shows the values for R^* and S^* based on fitting the hockey stick model to each of the 1,000 stock and recruitment data sets. Note that the value of S^* for each data set was constrained to lie within the range of spawning biomass levels for that data set. Figures 3.9and 3.10 show the marginal distributions for R^* and S^* respectively. The values for R^* and S^* are reasonably well-determined (CV=0.040 and 0.057 of R^* and S^* respectively) and positively correlated (ρ=0.51).

Generating occasional large recruitments

A key objective of this study is to capture the possibility and impact of occasional extreme recruitments, as well as the impact of "normal" variability in recruitment about the deterministic stock-recruitment model. Therefore, for each year of the projection period, the following procedure is applied to generate annual recruitment (age 2) for year y[6]:

Generate a random variable, Δ, from U[1,28] and compute the recruitment for year y expected from the stock-recruitment relationship, i.e.

$$\hat{R}_y = \begin{cases} R^* \dfrac{S_{y-2}}{S^*} & \text{if } S_{y-2} < S^* \\ R^* & \text{otherwise} \end{cases} \qquad (3.2.7)$$

If Δ is 26 or less, the year is a "normal" year (i.e. environmental conditions do not lead to extreme recruitments) and the recruitment for year y is generated based on the value of σ_R obtained from the residuals about the fit of the hockey stick model to the stock and recruitment data (ignoring the residuals for the 1982 and 1986 recruitments). The recruitment for year y is then generated from the expected recruitment according to the equation:

$$R_y = \hat{R}_y \, e^{\varepsilon_y - \sigma_R^2/2} \qquad \varepsilon_y \sim N(0;\sigma_R^2) \qquad (3.2.8)$$

If Δ is 27 or 28, an "extreme recruitment" is assumed to occur and the actual recruitment for year y is then generated according to the equation:

$$R_y = \hat{R}_y \, e^{v_\Delta + \varepsilon_y - \sigma_\tau^2/2} \qquad \varepsilon_y \sim N(0;\sigma_\tau^2) \qquad (3.2.9)$$

where v_{27} and v_{28} are, respectively, the largest and second largest residuals about the fit of the stock-recruitment model to the data. These errors assume recruitment

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[6] This presentation is predicated on a given selection of one of the 1,000 parameter sets for R^* and S^*.

residuals from R^* rather than from the stock-recruitment relationship. Thus, instead of three "extreme" recruitments (1982, 1986 and 2001), only two "extreme" recruitments (1982 and 1986) are considered.

The value of σ_R captures the impact of process error. Had σ_τ been assumed equal to σ_R, there is a possibility of unrealistically large recruitments (maximum recruitments are 50 to 210 billion fish recruitment under the assumption of R^*=0.7609, S^*=0.5610 and SSB=1.1428). Therefore, σ_τ is assumed to be 0.1 when generating "extreme" recruitments (i.e. when 28 or 27 is drawn from the uniform distribution for Δ). The sensitivity of the results to changing the value assumed for σ_τ is examined in Appendix 1.

It is necessary to calculate the unfished spawning stock biomass (B_0) as the spawning biomass-per-recruit in the absence of fishing multiplied by expected recruitment. The latter is given by:

$$\overline{R} = \frac{1}{28}[26R^* + R^* \exp(\nu_{27}) + R^* \exp(\nu_{28})] \qquad (3.2.10)$$

3.3 Economic Model

In this section, an economic model of the fishery for Pacific whiting is developed that can be used to interpret the results from the population dynamics model. The economic model incorporates the market value of the harvest and the cost of harvesting to determine the net economic value of fishing. The Pacific whiting fishery is a part of the multi-species, West coast groundfish fishery; fishers participate in the harvest of several species (e.g. salmon, halibut, and cod) during the year. The whiting fishery only operates within a limited time[7] during the year. Therefore, the fishery economics are modeled taking account of the budget of operators based only on the time they spend in the fishery for Pacific whiting.

Because the Pacific whiting fishery is conducted by mid-water trawlers during daylight hours only[8], rather than as a 24-hour continuous operation (e.g. the Alaskan Pollock fishery), the length of time spent is standardized by days fished. Fishing effort is therefore measured as days fished with a harvest capacity defined in the same units. This day-standardized fishing effort makes explicit the link between a vessel's economic activity and fishing mortality.

This study considers two economic models. The first, developed as part of this study, examines the economic effects to only U.S. shore-based sector and incorporates a penalty if the fishery has to be closed. The second economic model was based on that of Freese *et al* (1996) which aggregates harvesters and processors over the entire fishery.

This section first provides an overview of the economic components of the Pacific whiting fishery and then develops of an economic model for the U.S. shore-based harvesting sector. This section is followed by a description of the Freese *et al* (1996) model.

Economic component of the Pacific whiting fishery

Because of high levels of *myxosporidia* parasites and related protease enzymes, the harvest of Pacific whiting requires quick processing in order to ensure

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[7] The at-sea sector fishes for whiting between the Pollock A and B seasons (April-July) while the primary season for the shore-based fishery varies among ports: Newport and Astonia (June-October) and Crescent city (April – August).

[8] Pacific whiting rise to surface water during the day.

quality products (Sylvia and Enriquez, 1994). Consequently, Pacific whiting fishery operations are comprised of two diverse parts (harvesting and processing) which occur simultaneously. Heterogeneous fishing sectors with different emphasis in operations on these two parts co-exist in the current Pacific whiting fisheries.

The U.S. Pacific whiting fishery consists of three sectors: at-sea, shore-based and a tribal fishery by the Makah Indian Tribe (the Community Development Quota). The major difference between the at-sea and the shore-based fishery is the focus on processing: the at-sea fishery processes the product while at sea using on-board facilities, while the shore-based sector involves processing at coastal factories. The at-sea fishery consists of motherships and factory trawlers. Factory trawlers catch and process independently and usually do not have any associated catcher boats. In contrast, motherships engage approximately 4-10 catcher boats in harvesting operations and just process the harvest from the catcher boats. While the tribal fishery has a separate quota from the at-sea sector, it has the same operational structure as a mothership operation. In the shore-based operation, catcher boats deliver the harvest to land-based processing factories and involve approximately 4-8 catcher boats for every processing factory (Sylvia and Enriquez, 1994).

The Canadian Pacific whiting fishery consists of two sectors; shore-based and at-sea. Although catcher boats deliver product to both sectors, allocation regulations restrict their landings activities (see following section). The shore-based sector mainly involves four processing factories on Vancouver Island and was begun in 1991. The Canadian at-sea sector is operated by a joint venture (JV) with companies in foreign countries, mainly Poland and Russia. These companies are selected each season by bid. The Hake Consortium, which represents the Canadian harvest sector (catcher boats), selects partners according to three factors: 1) price (bid), 2) daily capacity and reliability of fleet, and 3) demonstrated ability to pay (Greer 2002).

Although the harvest-processing economic model of Freese *at al.,* (1996) is applied to all sectors, the focus of this study is on the catcher boats involved in the U.S. shore-based sector rather than the aggregated harvesting–processing operations of the other sectors. This focus was selected for two reasons.

a) The harvesting and processing operations of the shore-based sector can be distinguished as separate economic activities, but this is not the case for the at-sea sector. This economic separation relates to financial records and not to the physical functions of harvesting and processing. Operators in the U.S. shore-based sector involved in harvesting and processing are distinguished as catcher boats and shore-based processing factories respectively. In contrast, the earnings of catcher boats in the at-sea (mothership) operations is a share of processors' (i.e mothership's) net revenue rather than the direct earnings from selling their harvest[9]. In the case of factory trawlers, harvest and processing activities are aggregated, and cannot be distinguished as separate economic activities. In both at sea-sectors, therefore, it is difficult to estimate the value of harvesting independently from that of processing. Catcher boats in the shore-based sector, however, earn revenue by direct sales of harvest to processing factories. This allows the calculation of the net value of harvesting independently from that of processing (value addition).

b) The available data are not adequate to support models of other sectors, given the multi-sector fishery context. Since the nature of economic data in

[9] This recent trend is based on a risk-sharing business strategy in the market.

fisheries (e.g. operational cost, ex-vessel price) is confidential, we had difficulties in collecting adequate data to parameterize an economic model. Several economic surveys and studies (Pacific States Marine Fisheries Commission, 1998, Radtke, 1996, Parker, 2001, Wiedoff and Parker, 2002) have been conducted for the shore-based sector because it has local economical effects (e.g. employment, tax revenue) to coastal states (especially Oregon).

Harvesting activities are usually determined by the alternative options for fishing available to catcher boat operators given current fishing conditions (e.g. fish availability, the demands of the processors). This study, however, assumes the size of the harvest is determined by an allocated quota (i.e. operators always choose to operate in the fishery no matter how large their quota, how small the stock, and independently of harvest opportunities elsewhere). Therefore, as long as the relative proportion of the quota allocated to each sector remains constant, an index of economic returns based upon the operational costs and ex-vessel prices of the shore-based sector would be indicative of the economic status of the entire Pacific whiting fishery. The shore-based sector has lower ex-vessel prices (due to quality of product[10]), and higher operational costs[11] than the other sectors because of the longer delivery times to the processing facilities following harvesting. Although this may result in lower profitability for the shore-based sector and lead to the underestimation of actual profits from the Pacific whiting fishery, the economic return of the shore-based sector should be an adequate indicator of the overall returns of the Pacific whiting fishery. In a later section, however, this study makes

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[10] See ex-vessel price section for details.

[11] Although catcher boats in the at-sea sector deliver approximately three times each day, catcher boats in the shore-based sector can make at most only one delivery each day given the location of the whiting schools and the processing facilities (personal communication with Dr.Gil Sylvia, Oregon State University and Mr.Steve Parker, Oregon Department of Fish and Wild life, 2002).

use of the harvest-processor aggregated economic model developed Freese *el al* , (1996), to evaluate the economic return to the entire Pacific whiting fishery.

Allocation and utilization of quota

Allocation of Pacific whiting quota consists of two steps[12]: (a) the international allocation between the U.S. and Canada, and (b) the allocation of the U.S quota among domestic sectors. The U.S. and Canada were unable to agree how to allocate the harvest between them during the 1990s. As a result, since 1990, the total quota allocated to fishing sectors by the U.S. and Canada combined has exceeded 100% of the Allowable Biological Catch (ABC) suggested by the U.S. (Table 3.2). In 2002, agreement was reached between the U.S. and Canada to allocate the total harvest 74:26 between the U.S. and Canada. This international quota-share formula forms the basis for the current study.

In the U.S., the Pacific Fishery Management Council (PFMC) allocates the U.S. share of the total quota (80% in the past; 74% for the future) among the domestic sectors based on their historical catches. This domestic quota is allocated to the non-Tribal fishery (86%) and the Tribal fishery (14%). In 1997, a domestic allocation agreement divided the U.S. non-Tribal harvest between mothership operations (24%), factory trawlers (34%) and shore-based fisheries (42%) (PFMC, 1997). This allocation agreement was effective until 2001 and remained so for 2002. The management actions by the PFMC may preserve historical access and quota allocation within this fishery in the future. The future allocation of the U.S. domestic quota among sectors is therefore assumed to be the same as of 2002: at-sea (motherships) 14%, at-sea (factory trawlers) 29%, shore-based 36%, and Tribal

[12] Other than these two steps, factory trawlers have company allocations within their sector allocation; other sectors have an “Olympic” harvesting style within their sector allocation.

14% (Figure 3.11). The bioeconomic model relates to the economic consequences of the 36% quota share for the shore-based sector.

In Canada, the Minister of Fisheries allocates the Canadian part (26%) of the total quota to the harvesting sector (catcher boats). The allocation of the Canadian quota to the shore-based and JV operations depends on the landings activities of the catcher boats, which are regulated by the Hake Management Plan. Three key regulations are followed:

1) The first 50,000 (MT) of the quota must be allocated to the Canadian shore-based sector.
2) The first 50% of the remaining quota can be allocated as desired.
3) The last 50 % of the remaining quota is held to be allocated during the season.

Landing prices by joint venture operators are 2.5 times higher than those of shore-based operators because the product is of higher quality due to shorter delivery times and because these operators are subsidized by their home countries. Although catcher boats prefer to deliver to joint venture operators for this reason, Canada's Minister of Fisheries makes it a priority to deliver to shore-based processors to protect domestic industries (Greer 2002).

The allocated quota has not been fully-utilized in recent years (Table 3.3). This could be the result of two factors. First, a change to the migration pattern of Pacific whiting affected the availability of fish on the fishing grounds. Although Pacific whiting tended to migrate northwards during 1994-99, the La Nina in 1999-2000 apparently caused the population to shift to the south. As a result, most of the Pacific whiting stock migrated only as far north as the south of Washington State.

Low occurrence of Pacific whiting in Canadian waters resulted in only 25% of the Canadian quota being utilized (Helser *et al,* 2002). For the same reasons, the Makah Indians, who harvest close to Canadian waters, could not fully utilize their quota. Second, since 2000, the demand for Pacific whiting products may have decreased because of the prevalence of Mad Cow disease in Japan and Europe. Most of the Pacific whiting products go to the Surimi markets, and beef protein is required to produce Surimi because, without beef protein, the whiting flesh deteriorates quickly. Therefore, Pacific whiting products have shifted to lower profit markets, namely the Head &Gut and fillet markets. Consequently, processors appear not to have strong incentives to fully utilize their quotas. Although these two factors are problematic for current full utilization, this study assumes full utilization of quota in the future, unless processing capacity is limited.

Ex-vessel price

Ex-vessel price is defined as the price given to fishing vessels when the harvest is landed at the processing facilities. In this study, the ex-vessel price for the U.S. Pacific whiting fishery is defined as US$/ wet weight (kg) when catcher boats sell to motherships or shore-based processing factories.

Ex-vessel price varies with the demand for particular products and quantity of fish in the fish market. A price component is usually used in fishery bioeconomic models to adjust prices based on the quantities supplied by inverse demand curves (i.e. Thunberg *et al.*, 1998; Kennedy, 1992). However, Pacific whiting is mainly intended for the Surimi market, which is competitive, with a number of substitutions of other fish species. The proportion of Pacific whiting products in the Surimi market is relatively small (approximately 4% of worldwide

Surimi production originated from Pacific whiting products in 1997[13]). Therefore, the amount of Pacific whiting product on the market should not have a major influence on the ex-vessel price for Pacific whiting. An alternative to the demand model is constant price (i.e. Crarke *et al.*, 1992; Campbell *et al.,* 1993). This study assumes a constant ex-vessel price for Pacific whiting. Therefore, in this study, gross revenue is simply the ex-vessel price times the total harvest.

Figure3.12 summarizes the annual average ex-vessel prices of Pacific whiting between 1997-2000 from the PacFIN database[14]. Ex-vessel prices for the shore-based sector varied between \$0.050-0.095 / kg while those for the at-sea sector varied between \$ 0.079-0.229 / kg. Higher ex-vessel prices for at-sea processors may have resulted from the fact that the at-sea sector can process more fresh fish than shore-based facilities. This study uses the average of the 1997-2000 ex-vessel prices for the shore-based sector (\$ 0.084 / kg) as the future ex-vessel price.

Catch Per Trip (fishing effort)

This study assumes that catch per trip is constant (i.e. the catch per trip is independent of the abundance of the fish population). Catch in a fishery is often assumed to be related linearly to the abundance of the fish population, given the assumption of constant catchability (i.e. the same fraction of the total population is removed each haul)[15] (Hilborn and Walters, 1992, Thunberg *et al*, 1998). Under this model of the catching process, if the total biomass is assumed to be an indicator of the abundance of fish available to the shore-based sector, catch per day

[13] From #209:05-20-97 Justice Department Approves Fish Catches/Processors Proposal (U.S. department of justice, 1997).

[14] Pac FIN is the regional fisheries information network run by the Pacific States Marine Commission.

[15] Gunderson (1993) noted that catchability may be related inversely to fish abundance rather than being constant, at least a low stock size.

should be proportional to total biomass. Table 3.4 shows Pacific whiting landings for the shore–based sector in three States (Washington, Oregon and California), total number of trips and catch per trip. While the total biomass is estimated (Helser *et al.,* 2002) to have decreased by half (from 1.451 million tons in 1998 to 0.712 million tons in 2001), landings per trip did not change accordingly. This could be a result of innovation in commercial fisheries technology and improvement of navigational and positioning techniques to increase the effectiveness of fishing. These improvements allowed fishermen to locate fish schools or high abundance areas even under circumstances of low total biomass This study therefore considers catch per trip to be independent of the abundance of Pacific whiting. Further, because future changes in technology appear impossible to predict, catch per trip is also assumed to remain constant at recent levels, 70 MT per trip (the average of 1997-2002), irrespective of the future size of the resource. This catch per trip is combined with operational cost information (see the following section) to calculate the economic returns to the shore-based catcher boat sector.

Vessel operation costs

The construction of a cost model in fisheries always proves difficult due to inadequate data. This study estimated "typical" operational components/economic characteristics for a catcher boat from the "West Coast Catcher Boats Survey Summary 1997-1998" (Pacific States Marine Fisheries Commission, 1998), "Windows on Pacific Whiting – An Economic Success Story for Oregon's Fishing Industry" (Radtke, 1996) and the PacFIN database (PacFIN, 2002). The values that typify the cost associated with each cost category, based on these studies, were then modified using advice from vessel operators.

In these studies, average annual cost per catcher boat is only available for the entire West coast groundfish fishery. However, the Pacific whiting fishery is only one component of this fishery. Use of these data to develop a cost model for the shore-based fishery for Pacific whiting therefore requires calculating the operational cost per day fished based on the number of fishing days when involved in the Pacific whiting fishery.

Table 3.5 shows the estimated operational cost for a catcher boat per day fished. Variable costs, which depend on the duration of the operation (i.e. searching / fishing time, the number of trips), include payments to the crew and skipper, fuel and lube, and "other costs" (which include insurance for the crew and skipper). In Table 3.5, the duration of a fishing operation is standardized to "per day fished"[16]. Fixed costs, which are defined by fiscal year, include vessel- and gear-associated payments, insurance for vessel operations, recruitment and employment-associated costs, and "other costs" (which include mooring payments and administrative fees). These costs are also shown as "per day" in Table 3.5. In reality, the crew and skipper's wages are a share of the net income before subtracting labor costs and depend on ex-vessel prices and landed quantity. However, for simplicity, the cost model in this study assumes that these factors are constant, independent of catch and price.

Net economic return and loss during "non-fishing" years

Catch per trip and cost per day (operational costs) need to be combined to calculate the net economic returns. In 2002, the average number of days per trip was 1.77 (SD 1.39)[17]. Since vessels usually have to get in a queue in port due to constraints at the landing facility, the actual fishery operating time can be

[16] Unless the duration of operation is approximated as a day, the unit of variable cost should be associated with other units of the duration of an operation rather than per day unit. However, as shown later, the assumption that the shore-based sector effectively has a one-day operation is not a bad approximation.

[17] Personal communication from Dr. Steve Parker Oregon Department Fish and Wildlife (2002).

approximated as 1 day per a trip[18]. Consequently, the total operational cost per trip is assumed to be equal to the operational cost per day ($4,350 per trip; Table 3-5). Under the assumption of a 70 MT catch per trip, the gross revenue is $5,880 per trip ($0.084/kg multiplied by 70 MT/trip). Subtracting the operational cost per day from the gross revenue, the net economic return is calculated as $1,530 per trip. In other words, a 70 MT harvest leads to a $1,530 net return to a shore-based catcher boat.

In the simulations, the entire Pacific whiting fishery is closed if the estimate of the total biomass drops below a "minimum biomass level" which is part of the fishery management strategy. Although the variable costs associated with fishing do not occur if the fishery is closed, fixed costs still occur unless the catcher boats have alternative harvest opportunities. For the purposes of this study, fixed costs are assumed to occur in any "non-fishing" years. An average of 1,100 trips by the shore-based fishery took place during 1997-2002 (Table 3.4). Given the fixed cost per day ($2,150/day), this implies a cost of $2,365,000/year if the fishery is closed. In the simulations, this $2,365,000/year cost is applied to evaluate the loss caused by the fishery closing.

Processing capacity constraints

The Magnusson-Stevens Fishery Conservation and Management Act of 1976 led to Americanization of the fishing industry in the U.S. Excusive Economic Zone. This resulted in over-capitalization of the West coast groundfish fishery. Therefore, this study assumes that the harvest of Pacific whiting is not limited by the number of catcher boats. The processing capacity, however, is limited due to the limited mobility of facilities (shore-based) or limited working space on board

[18] Actual operation time may be 12-30 hours (personal communication with Dr. Gil Sylvia, 2002, Oregon State University)

factory trawlers and motherships. Some harvest strategies may yield TACs that are greater than the processing capacity. Therefore, this study incorporates processing capacity constraints on the harvest.

The Pacific Fishery Management Council (PFMC) (1997) estimated average daily harvesting/landing rates in the US factory trawl sector (10 vessels) at 3,600mt/day during 1994-96. The US mothership sector averaged 2,600mt/day and the US shore-based sector averaged 1,200 mt/day. While fleets don't typically fish continuously throughout the season, this can happen. Assuming May 15th is the opening date for all sectors (both US and Canadian), and the season lasts until mid-October, there are 150 total possible days of operation. This study assumes that the fleets lose 20% of those days to weather and other factors (*e.g.,* crew rest, maintenance, cleaning lines), leaving the full season at 120 days. Multiplying daily harvesting / landings rates for this full (120 day) season, allows the harvesting capacities of each sector to be calculated (see Table 3.6).

The US tribal fishery is assumed to be the same as one of the US factory trawlers (10 factory trawlers are operating , hence 10 % of US factory trawler sector) since one factory trawler acts as the mothership in the US tribal sector. The Canadian shore-based capacity is taken from Greer (2002). The capacity of the Canadian joint venture fishery is taken to be maximum historical catch by joint venture operations off the US and Canada (Helser *at al* 2002).

Another economic model for evaluating all sectors

Freese *et al* (1996) calculated the net economic benefit (US$/MT) to the US sectors (factory trawlers, mothership and shore-based) for a cost-benefit analysis used to develop a quota allocation formula for Pacific whiting. Although developed for the entire fishery, this model can be applied to the harvesting component of the US shore-based sector. Freese *et al.* (1996) calculated the total economic benefits of harvesting and processing (Table 3.7). This table assumes that the benefits to the Canadian shore-based sector are the same as those of the US shore-based sector. The benefits of the US tribal and Canadian joint venture sectors are assumed to be the same as those of the US mothership sector. While this model allows estimation of the entire economic effects of the Pacific whiting fisheries, it is unable to evaluate the impact of closing the fishery due to low biomass.

3.4 Monte Carlo Simulation - overview

Based on the population dynamics, stock-recruitment and economics models, 1000 simulations of a 50-year projection period are conducted for each harvest strategy (see the following Chapter for the details of the harvest strategies considered). The values for most of the biological parameters and the vector of numbers-at-age at the start of the 2001 (the first year of projection period) are taken from "Stock Assessment of Pacific whiting in US and Canadian Waters in 2001" by Helser *et al.* (2001) who conducted a Bayesian stock assessment of Pacific whiting (see Appendix 1). An overview of the simulation process is shown in Figure 3.13..

For each simulation of 50 years, values for S^* and R^* are chosen from the 1,000 calculated by fitting the hockey stick stock-recruitment model to 1,000 sets of 1972-2001 spawning stock biomass and recruitment data from the Bayesian stock assessment a (Figure 3.8). Given the values for S^* and R^*, it becomes possible to calculate unfished biomass (B_0), "normal" recruitment variance (σ_R^2), and the residuals needed when generating occasional "extreme" recruitments (v_{27}, v_{28}).

In each year of the projection period, an observed biomass is compared with a minimum biomass level. If the observed biomass exceeds the minimum level, a Total Allowable Catch (TAC) is calculated using the chosen harvest strategy (see the following chapter for the harvest strategies considered in this study). The total TAC is allocated to nation and sector as follows (see Figure 3.14).

1) The TAC is divided into quotas for the U.S. and Canada (76: 26). If the quota assigned to a nation exceeds its total harvest capacity, the difference between the quota and the harvest capacity is left unharvested

2) Within a nation, if the quota assigned to a sector exceeds its capacity, the difference is allocated to another sector within that nation.

The next chapter outlines the harvest strategies and the set of performance indicators used to evaluate performance.

Table 3.2. Negative log-likelihoods and parameter estimates for three stock-recruitment models

Model	-LnL	α	β / R^*
Hockey Stock	36.932	-	0.706
Ricker	37.790	1.147	0.483
Beverton-Holt	36.929	0.787	0.044

Table 3.2. U.S. and Canadian Pacific whiting quota (from Helser et al, 2002)

Year	ABC	U.S. quota(mt)	Canadian quota(mt)	Total quota (mt)	% of ABC for U.S quota	% of ABC for Canada	% of ABC for total quota
1988	327,000	232,000	98,000	330,000	71%	30%	101%
1989	323,000	225,000	73,500	298,500	70%	23%	92%
1990	245,000	196,000	98,000	294,000	80%	40%	120%
1991	253,000	228,000	98,000	326,000	90%	39%	129%
1992	232,000	208,800	90,000	298,800	90%	39%	129%
1993	178,000	142,000	61,000	203,000	80%	34%	114%
1994	325,000	260,000	110,000	370,000	80%	34%	114%
1995	223,000	178,400	76,500	254,900	80%	34%	114%
1996	265,000	212,000	91,000	303,000	80%	34%	114%
1997	290,000	232,000	99,400	331,400	80%	34%	114%
1998	290,000	232,000	80,000	312,000	80%	28%	108%
1999	290,000	232,000	90,300	322,300	80%	31%	111%
2000	290,000	232,000	90,300	322,300	80%	31%	111%
2001	238,000	190,400	81,600	272,000	80%	34%	114%

Table 3.3. Utilization of quota (modified from Helser et al, 2002)

	US Total harvest (1000t)	US Quota (1000t)	**US Utilization (%)**	Canada Total harvest (1000t)	Canada Quota (1000t)	**Canada Utilization (%)**
1988	160.7	232.0	**69%**	90.5	98	**92%**
1989	211.0	225.0	**94%**	99.5	98	**102%**
1990	183.8	196.0	**94%**	76.7	73.5	**104%**
1991	217.5	228.0	**95%**	104.5	98	**107%**
1992	208.6	208.8	**100%**	86.4	90	**96%**
1993	141.2	142.0	**99%**	58.9	61	**96%**
1994	252.7	260.0	**97%**	106.2	110	**97%**
1995	177.6	178.4	**100%**	70.4	76.5	**92%**
1996	212.9	212.0	**100%**	88.2	91	**97%**
1997	233.4	232.0	**101%**	90.6	99.4	**91%**
1998	232.5	232.0	**100%**	86.7	80	**108%**
1999	223.5	232.0	**96%**	86.6	90.3	**96%**
2000	208.4	232.0	**90%**	22.3	90.3	**25%**
2001	182.4	190.4	**96%**	53.3	81.6	**65%**

Table 3.4. Annual landings and number of trips for the shore-based Pacific whiting fishery(from Shoreside Whiting Operation Program reports: 1997- 2002)

Year	Number of catcher boats[1]	Landings (MT)	Number of trips	landing per trip (MT)
1997	40	85,984	1,356	63.41
1998	38	87,434	1,348	64.86
1999	36	83,272	1,216	68.48
2000	35	85,404	1,066	80.12
2001	29	73,262	1,013	72.32
2002	29	45,276	627	72.21
Average			**1,100**	**70.23**

Table 3.5. Estimated operational cost of a catcher boat

Variable Costs	Payment to the crew and skipper	**$1,250**	per day[19]
	Fuel and lube	**750**	per day
	Other costs	**$200**	per day
Fixed Costs	Vessel and gear associated payments	**$1,000**	per day
	Insurance associated with vessel operation	**$300**	per day
	Recruitment, travel, benefits and other employee-related costs	**$50**	per day
	Other costs	**$800**	per day
	Total of variable and fixed costs	**$4,350**	per day

[19] See reference 11.

Table 3.6. Processing capacity of Pacific whiting fishery

Sectors	Annual capacity for processing (MT)
US factory trawlers	432,000
US motherships	312,000
US shore based	144,000
US tribal	43,200
Canada shore based	122,400
Canada joint venture	269,834

Table 3.7. Economic benefits from harvest for each sector Freese *et al.,* 1996

Sectors	Economic benefits from harvest (US$/MT)
US factory trawlers	248
US motherships	169
US shore based	146
US tribal	169
Canada shore-based	146
Canada joint venture	169

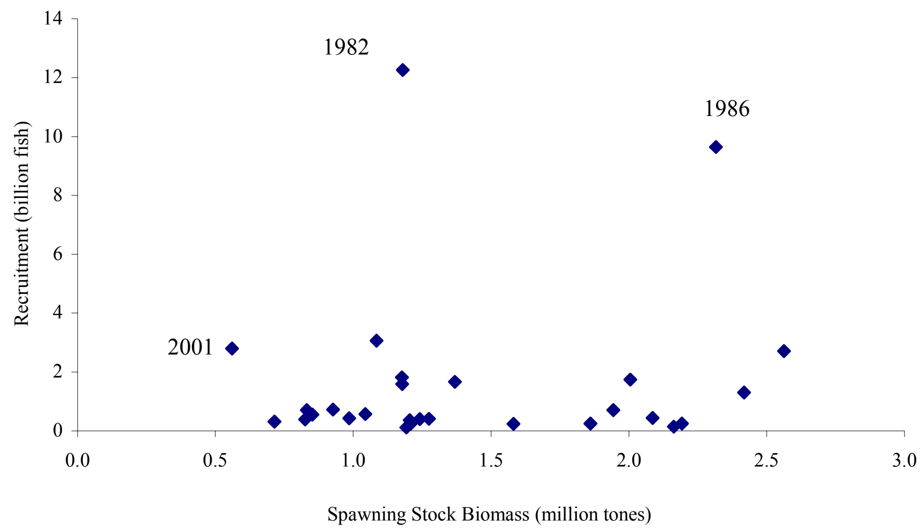

Figure 3.3. The maximum likelihood estimates of Pacific whiting spawning stock biomass and recruitment (from Helser *at al,* 2002)

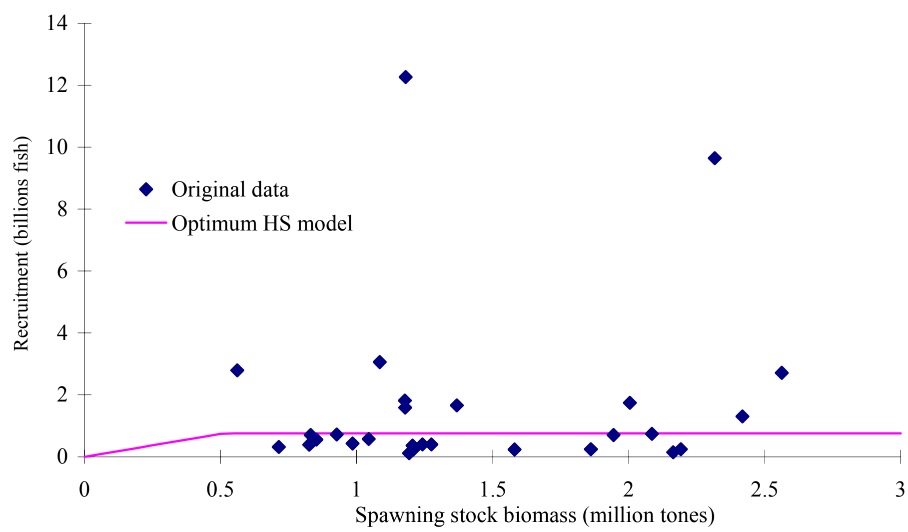

Figure 3.4. Fit of the hockey stock model to the spawning stock biomass and recruitment data for Pacific whiting (maximum likelihood estimates)

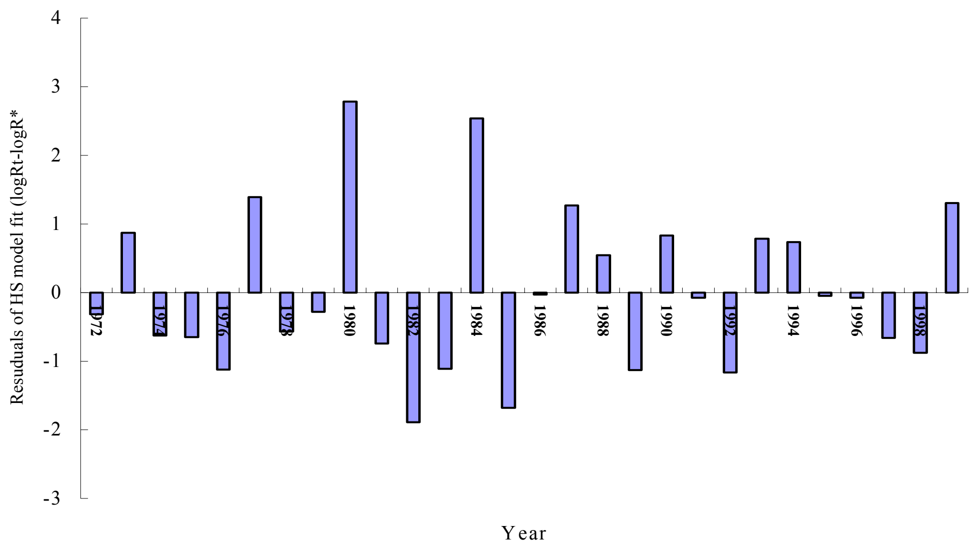

Figure 3.3. Residuals about the fit to the maximum likelihood estimates of annual recruitment of Pacific whiting

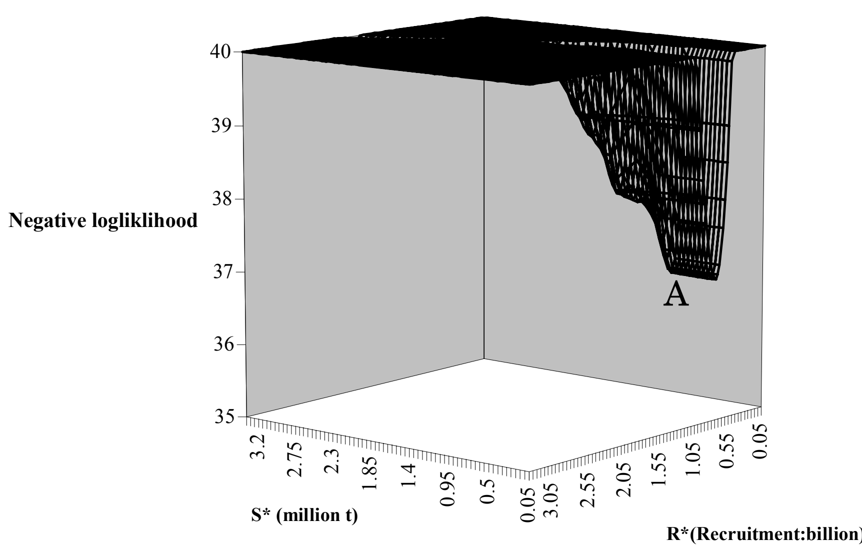

Figure 3.4. The negative log likelihood surface.

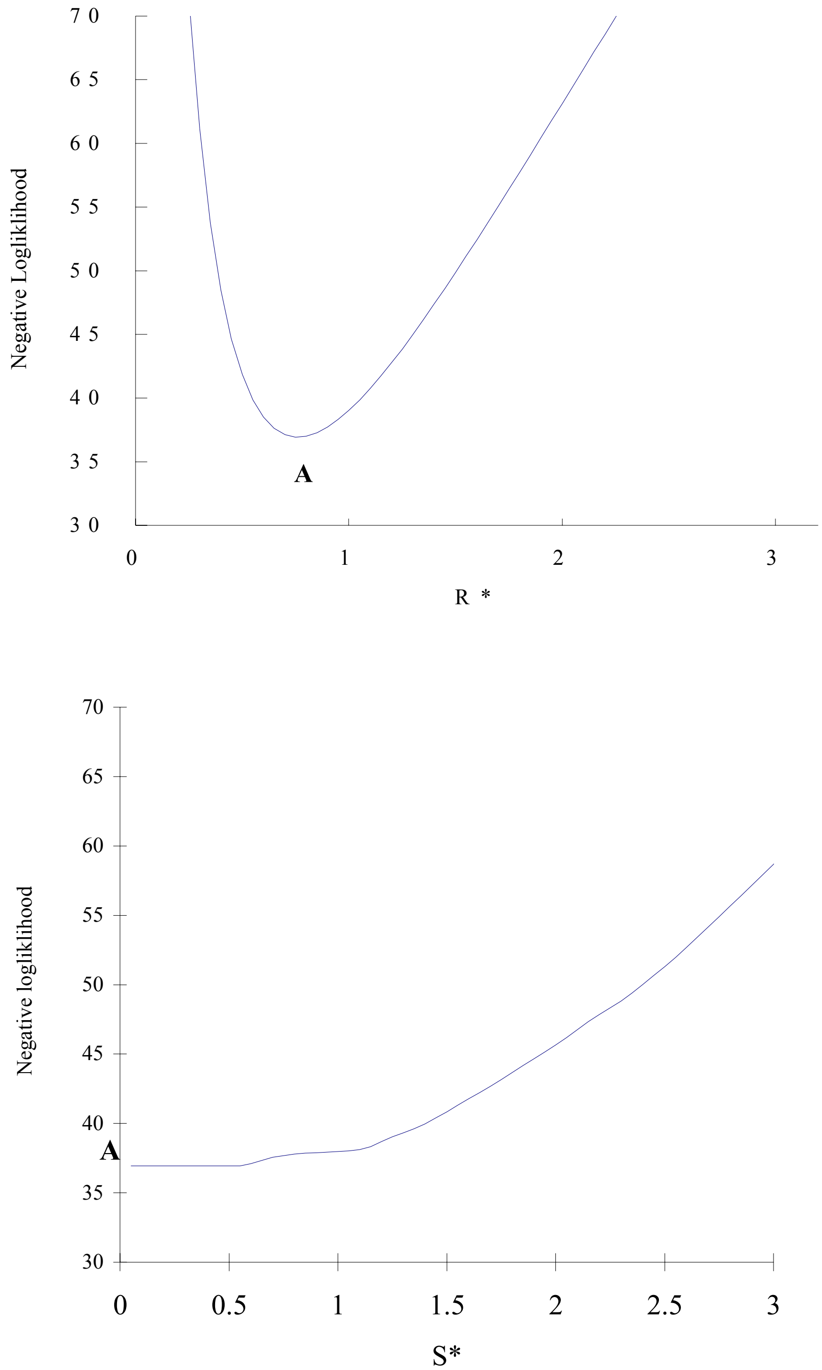

Figure 3.5. Likelihood profiles for (a) *R** and (b) *S**

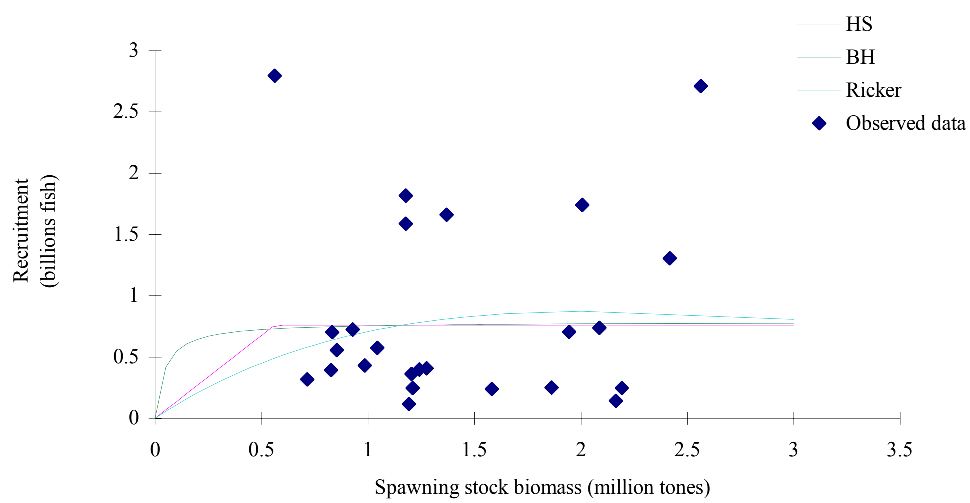

Figure 3.6. Fits of three stock-recruitment models to the spawning stock biomass and recruitment data for Pacific whiting (maximum likelihood density estimates).

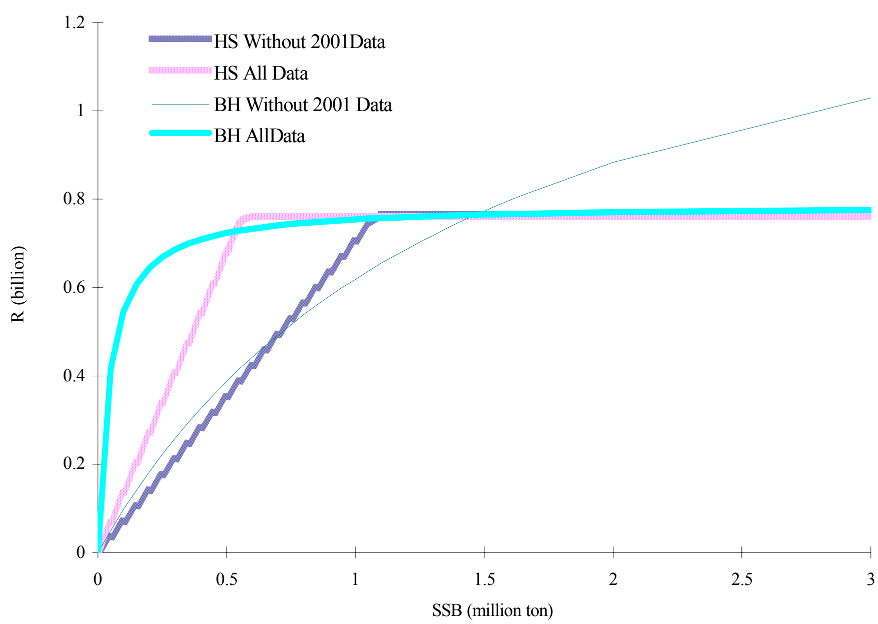

Figure 3.7. Illustration of the effect of including / excluding the 2001 data point on the fits of the hockey stick (HS) and Beverton-Holt (BH) stock-recruitment models

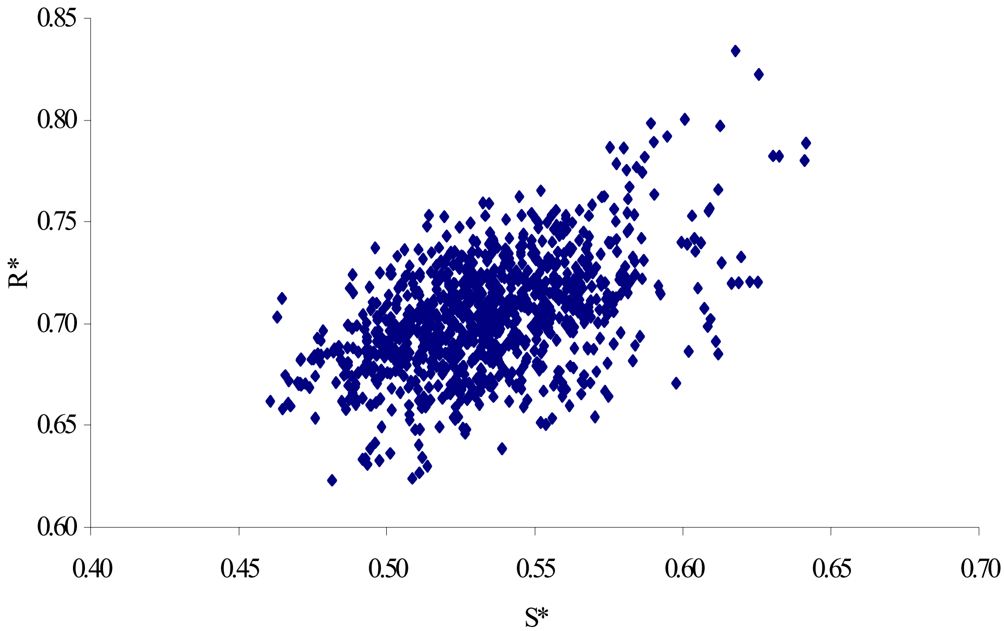

Figure 3.8. The 1,000 parameter vectors based on fitting the hockey stick model to data sets generated from a Bayesian posterior distribution.

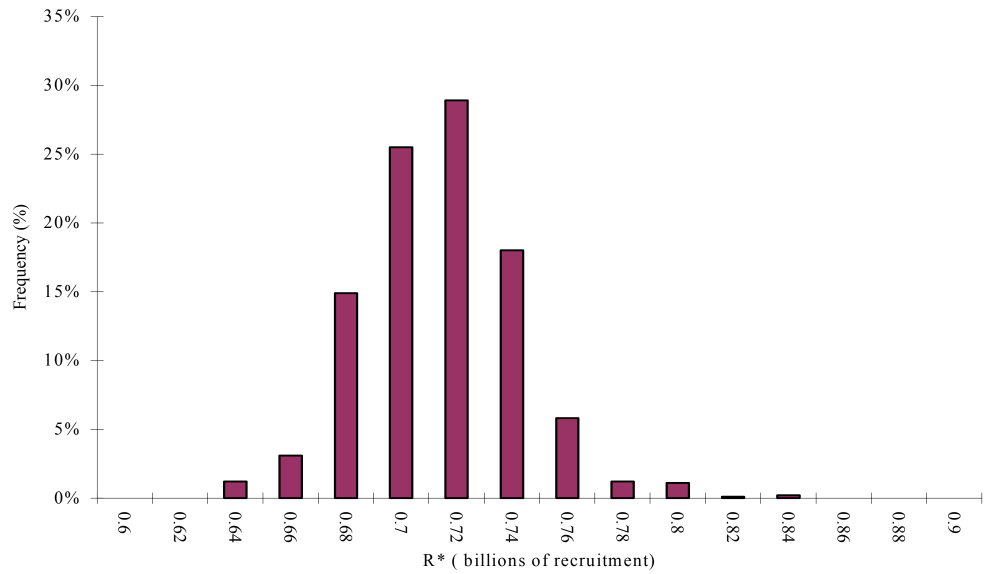

Figure 3.9. The marginal distribution for *R**.

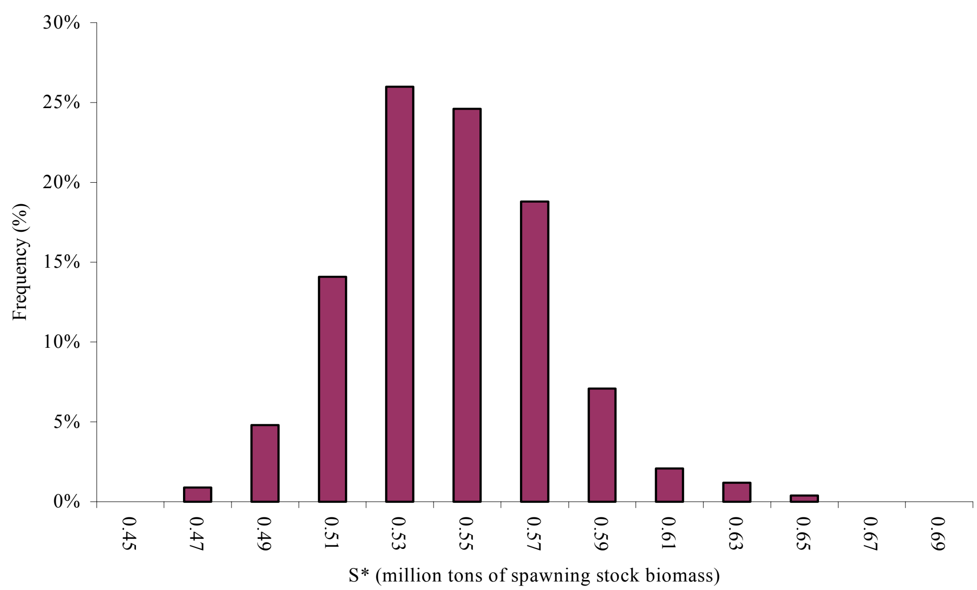

Figure 3.10. The distribution of S*.

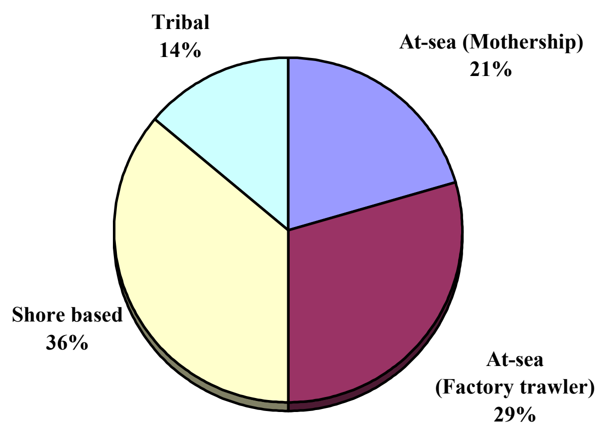

Figure3.11. Allocation of the U.S. Pacific whiting fishery quota among U.S. domestic sectors

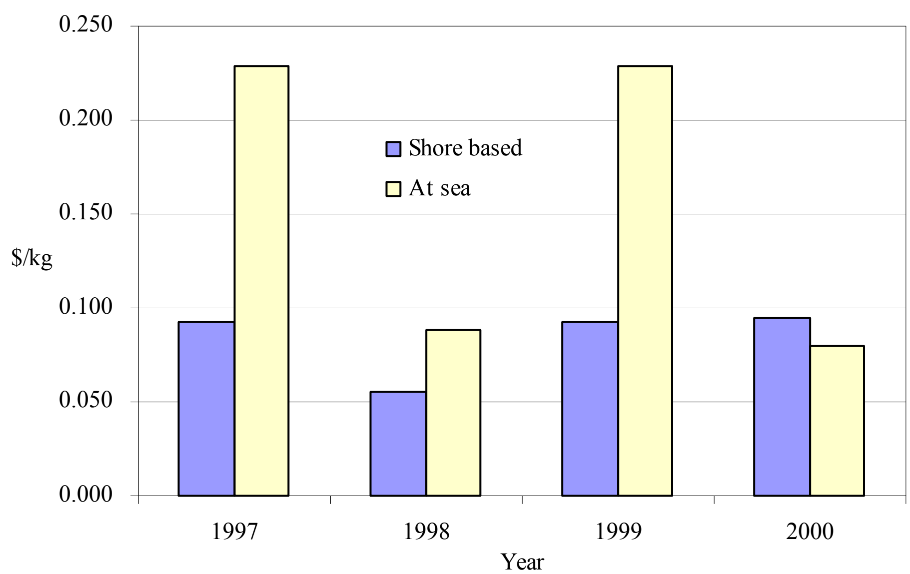

Figure 3.12. Annual ex-vessel price of Pacific whiting (US$/kg) between 1997-2000 (modified from PacFIN)

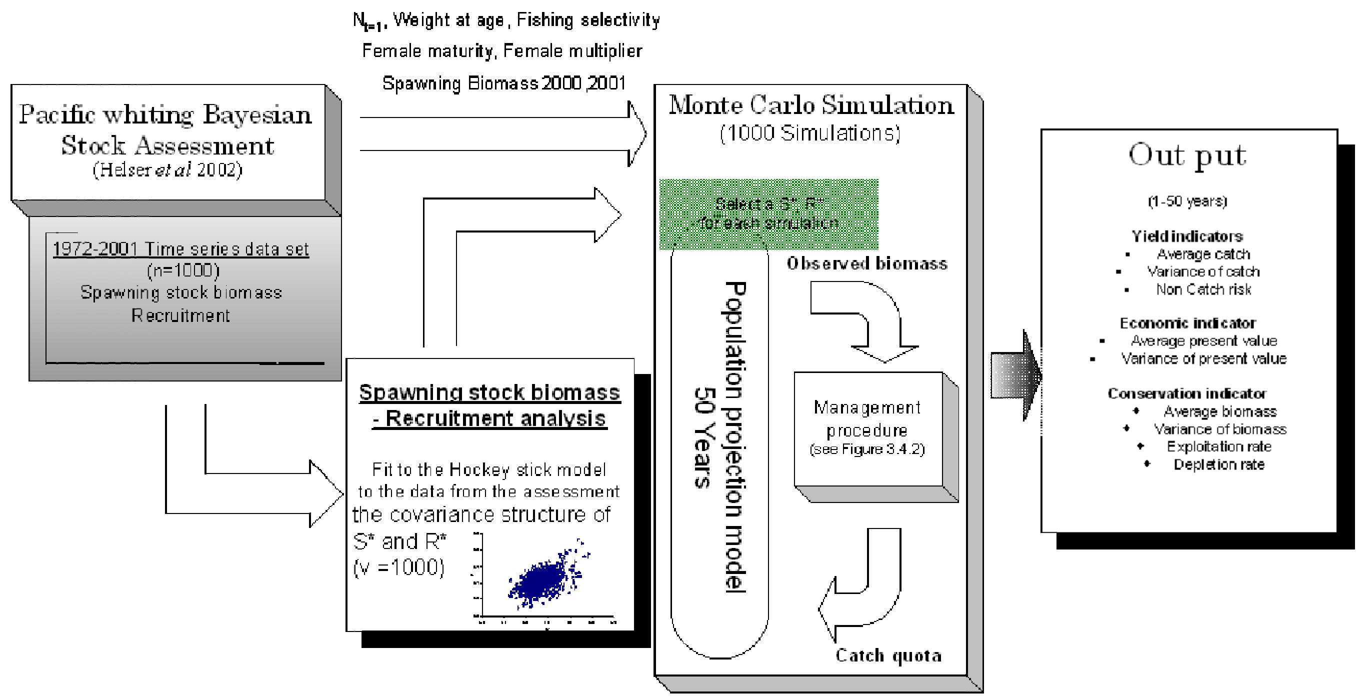

Figure 3.10. Overview of Pacific whiting fishery bioeconomic simulation.

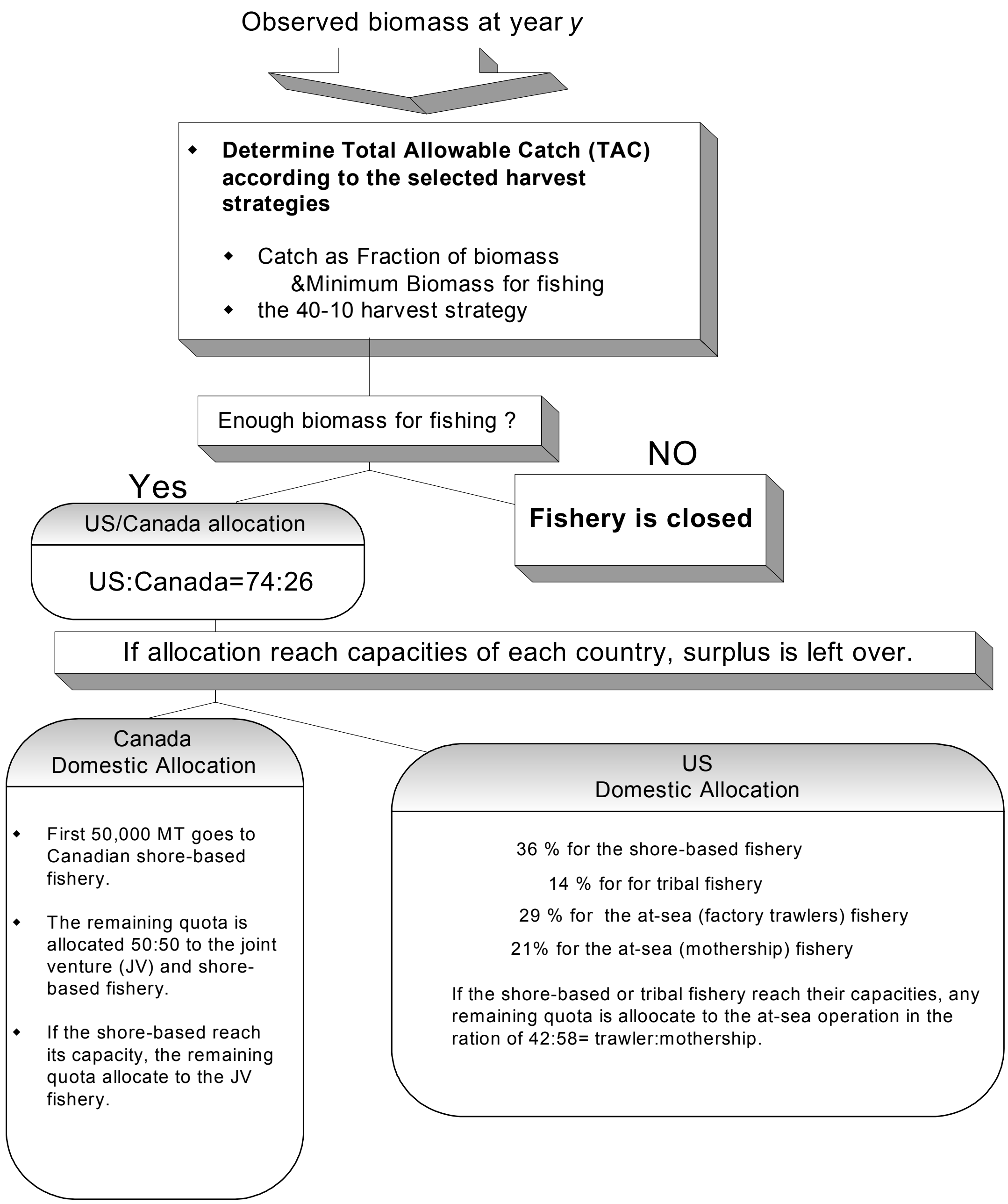

Figure 3.14. Management model over view

Chapter 4: Harvest strategies and performance indicators

Since direct fishing is an essential part of any fishery, the core of a fishery policy is harvest management, which may include harvest quotas, gear restrictions, area and seasonal closures, and other elements. In US fisheries, the harvest quota is often assigned on an annual basis and is called “total allowable catch” (TAC) or “optimum yield” (OY). In some fisheries, such as the Pacific whiting fishery, the harvest quota is calculated from an agreed formula (established in the fishery management plan) that assigns a TAC based upon the annual stock assessment, using a formula for spawning potential (or spawning stock biomass (SSB)) into TAC.

Such a formula is called a “harvest strategy” to indicate that it implies a response to changing estimated biomass over time. Decision makers (i.e., fishery managers) must consider various biological, economic, and social factors in adopting a specific harvest strategy. Alternative harvest strategies may have varying results in terms of average and variance of catch, spawning stock biomass, economic returns and other indicators of fishery performance. Population dynamics and economic models are needed to examine the performance of a suite of possible harvest strategies (National Research Council 1998).

This chapter; (1) examines the concepts of harvest strategies and explains the current strategy adopted by the Pacific Fishery management Council for the Pacific whiting fishery, (2) explains how the annual biomass assessment is modeled in order to evaluate alternative harvest strategies, and (3) describes a set of performance indicators developed to evaluate harvest strategies in a Monte Carlo simulation model.

4.1 Harvest strategies

Two types of harvest strategies are commonly used in fisheries management (Hilborn and Walters 1992; National Research Council 1998; Quinn and Deriso 1999);

1) Fixed exploitation rate:

A fixed exploitation rate strategy involves setting the annual catch equal to a constant fraction of the current biomass. The size of the catch, therefore, is always proportional to the size of the biomass and so the catch reflects stock fluctuations directly.

2) Constant escapement (surplus production policy):

A constant escapement strategy attempts to conserve the fish stock from a renewable resource point of view. This harvest strategy sets the catch limit equal to the difference between the current biomass and some minimum biomass, where the minimum biomass is chosen to achieve goals related to conservation, rebuilding or reducing biomass size.

While these two harvest strategies have been discussed extensively in the fisheries management literature, the fisheries bioeconomic literature has discussed two different fishing strategies (*e.g.,* Hanneson 1993; Steinshamn 1998): 1) constant catch, and 2) constant effort.

The main goal of a fisheries bioeconomic approach is to evaluate economic return (or the present value of the economic return) rather than the simple set of yield / conservation measures (*i.e.,* average catch, spawning stock biomass). Economic return is the difference between gross revenue and total cost (operational + fixed cost). In general, catch-per-unit-of-effort drops as biomass decreases.

Lower biomasses therefore lead to higher operational costs in order to maintain a constant catch. In the face of decreasing biomass, a constant effort strategy leads to lower catches (though not necessarily lower revenue because price could be determined by a combination of supply and demand). In contrast, catch-per-unit-of-effort increases as biomass increases so that operational costs would decrease if the catch was constant and would increase if effort did not change in response to increased biomass.

This study considers two harvest strategies: 1) a strategy in which the catch limit is zero if the biomass is less than the minimum biomass allowed for fishing permissive fishery, and the fraction of the difference between the current biomass and the minimum biomass if the current observed biomass exceeds the minimum biomass (the “Fraction/Minimum biomass” strategy), and 2) ’40-10’ harvest strategy.

The first strategy, which could be considered to be a combination of the fixed exploitation rate and constant escapement strategies, is used to evaluate the trade-off between mean catch / economic return and variance in catch / economic return. The second strategy is that actually used by the Pacific Fishery Management Council and is examined to allow comparison of the current approach with the “Fraction/Minimum biomass” strategy.

Biomass-based harvest strategies

The “Fraction/Minimum biomass” strategy includes the biological reference point that depends on B_0[20], the unfished 3+ biomass.

The “Fraction/Minimum biomass” harvest strategy defines the TAC as:

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[20] Also called virgin biomass

$$TAC_y = \max\left[0, \left(\hat{B}_y - \text{Minimum Biomass}\right)\text{Fraction}\right] \qquad (4.1.1)$$

Equation (4.1.1) implies that the fishery will be closed if the biomass is estimated to be less than the minimum biomass and that the catch limit will increase linearly with biomass increased if the biomass is estimated to be larger than the minimum biomass (Figure 4.1). Many "modern" fisheries harvest strategies involve fishing mortality reference points (*e.g.,* $F_{MSY}, F_{med}, F_{40\%}$) to calculate the "optimal" catch or fishing effort. The "Fraction/Minimum biomass" harvest strategy is simple because the TAC increases in proportion to biomass. This harvest strategy is appropriate for examining the direct consequences on catch of fluctuations in biomass.

The combination of a higher minimum biomass and a lower fraction places greater emphasis on stock conservation. In other words, if the management objective is stock conservation, the manager should choose a high minimum biomass and low fraction (Figure 4.2). A total of 110 combinations of 11 fractions $\{0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0\}$ and 10 minimum biomasses $\{0.05B_0, 0.1B_0, 0.2B_0, 0.3B_0, 0.4B_0, 0.5B_0, 0.6B_0, 0.7B_0, 0.8B_0, 0.9B_0\}$ are considered in this study.

In choosing a minimum biomass, account should be taken of a species' compensatory ability at low biomass level. That is, with higher compensation (greater growth potential at low biomass) the minimum biomass can be set as lower values (Quinn *et al,* 1990).

Current harvest strategy for the Pacific whiting fishery

The Pacific Fishery Management Council (PFMC) adopts a Fisheries Management Plan (FMP), which contains measures for conserving and managing fisheries (Helser *et al* 2002). The '40-10' rule is designed to be consistent with the National Standards Guidelines (NSG) established by the Sustainable Fisheries Act because fishing mortality is never permitted to exceed F_{msy} (i.e. overfishing is avoided).

The '40-10' rule for the Pacific whiting is expressed as follows:

$$OY_y = \begin{cases} F_{msy}\, SSB_y & \text{if } SSB_y / B_0 > 0.4 \\ F_{msy} \dfrac{0.4 SSB_y (SSB_y / B_0 - 0.1)}{0.3\, SSB_y / B_0} & \text{if } 0.1 \le SSB_y / B_0 \le 0.4 \\ 0 & \text{if } SSB_y / B_0 < 0.1 \end{cases} \qquad (4.1.2)$$

where OY_y is the optimum yield for year y,

F_{msy} is the fishing mortality corresponding to Maximum Sustainable Yield, *MSY*, and

SSB_y is the spawning biomass at the start of year y.

F_{msy} is defined as the fishing mortality that reduces spawning biomass-per-recruit (SPR) to the level at which *MSY* is assumed to occur. For Pacific whiting, this level is 40% of the SPR in the absence of fishing (National Research Council 1998). Dorn *et al*. (1999) concluded that *MSY* for Pacific whiting occurs at 40-45% of the virgin SPR using a Bayesian meta-analysis of *merluciid* species in which the stock-relationship was assumed to be of the Beverton-Holt form.

The '40-10' rule reduces the exploitation rate if the stock is less than 40% of B_0 and closes the fishery if the spawning biomass is less than 10% of B_0 (Figure 4.3). The '40-10' rule is therefore similar to the "Fraction/Minimum Biomass" harvest strategy, except that the '40-10' rule is based on spawning biomass rather than 3+ biomass.

Modeling Biomass Estimation for Pacific whiting

The TAC for Pacific whiting is calculated using an estimate of the spawning stock biomass (SSB). The default proxy for spawning stock biomass used in this study is the biomass of fish aged 3 and older (the 3+ biomass), unless specified otherwise. The biomass on which the TAC is based is not the actual 3+ biomass but rather an estimate of this biomass ($\hat{B}_y$). $\hat{B}_y$ is determined by adding the temporally auto-correlated normally-distributed observation error with coefficient of variation, CV of 0.15[21] to the actual 3+ biomass, i.e.:

$$\hat{B}_y = B_y(1+\eta_y) \qquad \eta_y = \rho\eta_{y-1} + \sqrt{1-\rho^2}\,\xi_y \qquad \xi_y \sim N(0;\sigma_\theta^2) \qquad (4.1.3)$$

where ρ is the extent of temporal auto-correlation in the observation errors, and σ_θ is the standard deviation of the observation errors (taken to be 0.15). The value η_y for y=1 is generated from $N(0;\sigma_\theta^2)$.

Temporally auto-correlated observation error is considered because observation errors are not independent; over-estimation of biomass in one year will usually imply over-estimation of biomass in the following year and *vice versa*. ρ,

[21] This is the CV for the biomass estimates based on the Bayesian assessment of Pacific whiting.

the extent of temporal auto-correlation in observation error, is assumed to be 0.5 (see appendix 3 for sensitivity of to the results of value of ρ).

Given the expected recruitment in the absence of exploitation (1.438 billion fish - Equation 3.2.10), B_0 is 3.967 million tons (Table 4.1). The current Pacific whiting stock assessment estimates SSB at B_0 to be 2.088 million tons (Helser *et al* 2002) based on an average recruitment between 1972 and 2001 of 1.708 billion fish. The estimate of SSB at B_0 reported in Table 4.1 (2.02 billion tons) is calculated from the maximum posterior density estimate of the expected recruitment in the absence of exploitation. This estimate of B_0 is 96.8% of that reported by Helser *et al*. (2002). When conducting the future projections, different values for S^* and R^* are selected for each simulation. One result of this is that B_0 differs among simulations.

4.2 The performance indicators

Fisheries provide benefits not only to the fishing industry, but also lead to societal benefits. For example, stock conservation measures are usually designed to ensure that future benefits accrue to society. Therefore, it can be argued that the objective of fisheries management is to maximize benefits to society now and in the future.

The bioeconomic approach to fisheries management considers “benefits to society” in several ways (*e.g.,* economic return, maximum economic yield) rather than just in terms of the traditional biological objective of maximizing the yield. In addition, consideration needs to be given to conserving the fish stocks targeted, and the ecosystems on which they depend. This implies that there are multiple objectives that fisheries management needs to consider explicitly.

Simulations, such as those on which this study are based, enable each alternative harvest strategy to be evaluated in terms of how well it satisfies the management objectives. However, in order to achieve this, it is necessary to define performance indicators that summarize the key outputs from the simulations in terms of these objectives. This section develops the set of performance indicators for the simulations.

Three categories of performance indicator are considered: 1) conservation/biomass indicators, 2) yield indicators, and 3) economic indicators. All of the indicators are based on 1,000 simulations of a 50 year projection period. In addition to reporting the means for each indicator, the among-simulation variability is quantified by means of the among-simulation standard error of the indicator.

Yield indicators

The mean and standard deviation of catch (MT) for *th* harvest strategy are calculated as follows:

$$\overline{C}_{th} = \frac{1}{N_{sim}} \sum_{k=1}^{Nsim} \frac{1}{50} \sum_{y=1}^{50} C_y^k \qquad (4.2.1)$$

$$\overline{C}.SD_{th} = \frac{1}{N_{sim}} \sum_{k=1}^{Nsim} \left(\frac{1}{49} \sum_{y=1}^{50} \left(C_y^k - \frac{1}{50} \sum_{y'=1}^{50} C_{y'}^k \right)^2 \right)^{\frac{1}{2}} \qquad (4.2.2)$$

where C_y^k is the catch during year *y* in simulation *k*, and

N_{sim} is the number of simulations (1,000).

When the observed biomass is below the minimum biomass, the fishery is closed (see Figure 4.1). The "NonCatchRisk" for *th* harvest strategy is the average percentage of years in which the fishery is closed, i.e.:

$$NonCatchRisk = \frac{100}{N_{\mathrm{sim}}} \sum_{\mathrm{i}=1}^{\mathrm{N_{sim}}} \frac{1}{50} \sum_{y=1}^{50} I(C_y^k = 0) \qquad (4.2.3)$$

where $I(C_y^k = 0)$ is an indicator which is 1 if the catch during year *y* in simulation *k* is zero. and zero otherwise.

Economic indicators

The present value of the net economic return over the 50-year projection period is taken as the measure of economic performance. The average and standard deviation of the present value for *th* harvest strategy are:

$$\overline{PV}_{th} = \frac{1}{N_{sim}} \sum_{k=1}^{N_{sim}} PV^k \qquad (4.2.4)$$

$$PV.SD_{th} = \left(\frac{1}{N_{sim} - 1} \sum_{k=1}^{N_{sim}} \left(PV^k - \overline{PV}_{th} \right)^2 \right)^{\frac{1}{2}} \qquad (4.2.5)$$

where PV^k is the net present value in the k^{th} simulation:

$$PV^k = \sum_{y=1}^{50} \frac{1}{(1+d)^{y-1}} NER_y^k$$

d is the discount rate (taken to be 0.032 because the U.S. Office of Management and Budget[22] suggests the use of a 3.2% discount rate for 30-year cost-effectiveness analysis), and

NER_y^k is the net economic return of harvest during year y in simulation k (equal to US$1,530/70 multiplied by C_y^k if the catch for year y and simulation k is non-zero and –US$2,365,000 if the fishery is closed).

Conservation/biomass indicators

The average and standard deviation of (3+) biomass for harvest strategy *th* ($\overline{B}_{th}$ and $B.SD_{th}$ respectively) are calculated over years and simulations:

$$\overline{B}_{th} = \frac{1}{N_{sim}} \sum_{k=1}^{Nsim} \frac{1}{50} \sum_{y=1}^{50} B_y^k \tag{4.2.6}$$

$$B.SD_{th} = \frac{1}{N_{sim}} \sum_{k=1}^{Nsim} \left(\frac{1}{49} \sum_{y=1}^{50} \left(B_y^k - \frac{1}{50} \sum_{y'=1}^{50} B_{y'}^k \right)^2 \right)^{\frac{1}{2}} \tag{4.2.7}$$

where B_y^k is the true (not observed) 3+ biomass at the start of year y in simulation k.

The average exploitation rate (expressed as a percentage) for the *th* harvest strategy is given by:

$$E_{th} = \frac{100}{N_{sim}} \sum_{k=1}^{Nsim} \frac{1}{50} \sum_{y=1}^{50} \frac{C_y^k}{B_y^k} \tag{4.2.8}$$

[22] http://www.whitehouse.gov/omb/circulars/a094/a94_appx-c.html. This value is available until January 2004.

The average depletion rate over the 50-year projection period (expressed a percentage) for the *th* harvest strategy is:

$$D_{th} = \frac{100}{N_{sim}} \sum_{k=1}^{N_{sim}} \frac{1}{50} \sum_{y=1}^{50} \frac{B_y^k}{B_0^k} \qquad (4.2.9)$$

where B_0^k is B_0 (in terms of 3+ biomass) for simulation *k*.

4.3. Harvest strategy evaluation

Given the estimated parameters for the Pacific whiting population and fishery economic models, the simulation model generates large data for biomass, yield, and economic indicators described in this chapter, for each of the harvest strategies. These results can be used to compare and evaluate the harvest strategies.

Economics literature on risk and uncertainty (Zerbe and Dively 1994) suggested that variability in annual economic return (or 50-year net present value, in the case of this study) is disadvantageous. Fishery managers and people in fishery industries tend to prefer a higher mean return or present value, but they are averse to the risks and expenses associated with variability in annual harvest and in variability within present values due to the presence of process and measurement errors. For example, maintaining a given mean annual yield in the face of variance requires that the fishing industry maintain a higher cost. This would, in a full model of fishery investments, be reflected in a higher catch and processing capacity needed for harvest strategies that entail greater annual variability in catch.

Second, investments in capital equipment and crew plus processor training /skills are required to maintain harvest capacity. These investments are made by vessel owners, processing plant owners, and laborers in expectation of future earnings. The present value of annual net economic values represents this expectation in our Pacific whiting bioeconomic model. When the present value varies across 50-year simulations, this reflects uncertainty in the returns on investments made for fishery industries. Higher inherent risks to investors must balance against expected earning to investors. That is, in the market for investment funds, greater risk must be rewarded by a higher expected rate of return on investment. In our model we do not calculate the compensatory payment that would be needed to compensate for the variance in present value for each harvest strategy. Instead, we simply display the trade-offs between mean and variance (in catch and present value) inherit in the alternative harvest strategies. These trade-offs are useful as information to both industry participants and fishery managers in the process of deciding which harvest strategies are worthy of consideration.

Beside the trade-off mean and variance, "stochastic dominance" occurs when two harvest strategies have the same average catch or net present value, but one has less variability. When catch or net present value for one harvest strategy dominates another, in regard to the level of variability, it can be called "stochastic dominance" (a first –degree stochastic dominance) (Zerbe and Dively 1994). Fishery managers and industry prefer less variability in catch or net present value. In turn, the stochastic dominance in catch or net present value is useful information for evaluating harvest strategies.

Table 4.3. B_0 based on the maximum likelihood estimates by Helser *et al.,* 2002 and various percentages of B_0

	3+ Biomass (million tones)	SSB (million tones)	
B_0	**3.967**	2.021	
$B_{90\%}$	**3.570**	1.819	
$B_{80\%}$	**3.174**	1.617	
$B_{70\%}$	**2.777**	1.415	
$B_{60\%}$	**2.380**	1.213	
$B_{50\%}$	**1.984**	1.010	
$B_{40\%}$	**1.587**	0.808	
$B_{30\%}$	**1.190**	0.606	
$B_{20\%}$	**0.793**	0.404	
$B_{10\%}$	**0.397**	0.202	
2001	**0.712**	0.415	**18% of B_0**

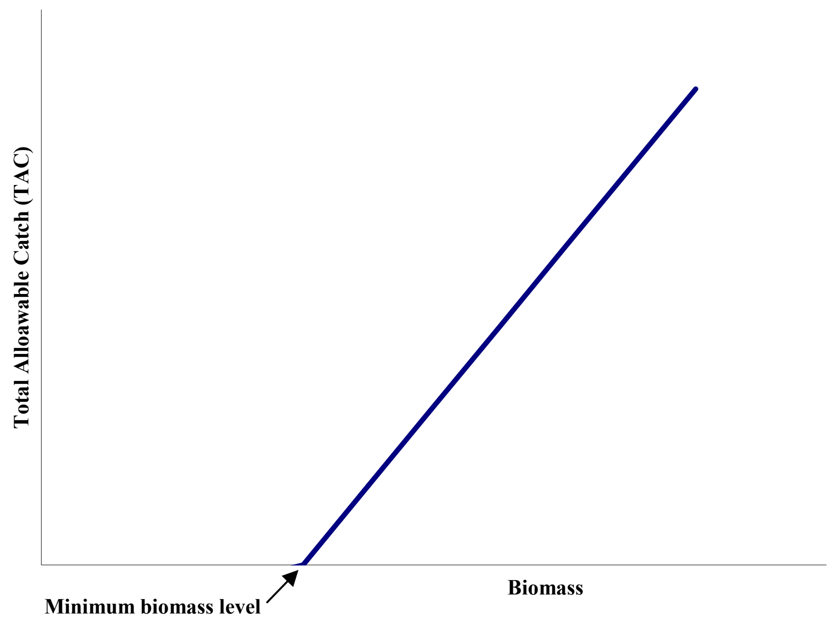


Figure 4.1. “ Fraction/Minimum Biomass” harvesting strategy

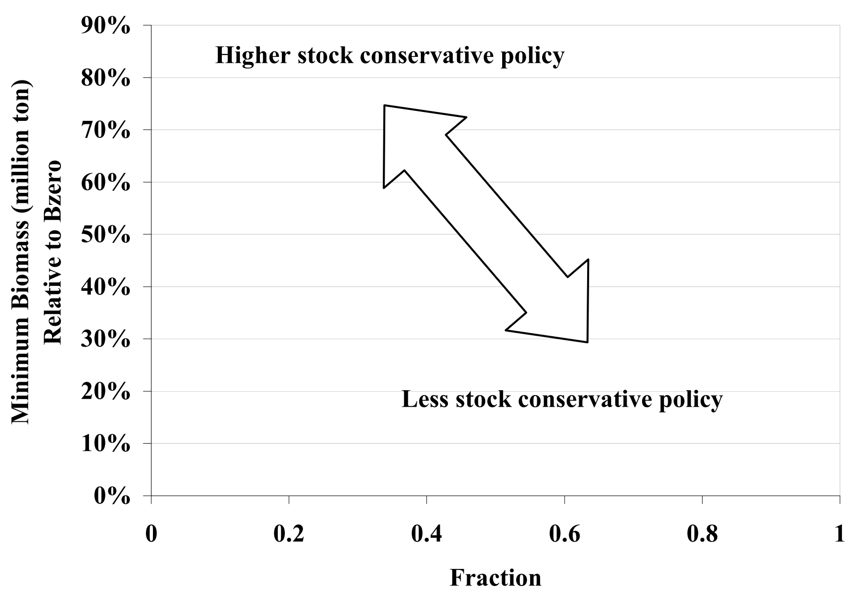


Figure 4.2. The relationship between the parameters of the “Fraction/Minimum Biomass” harvesting strategy and the extent of stock conservation

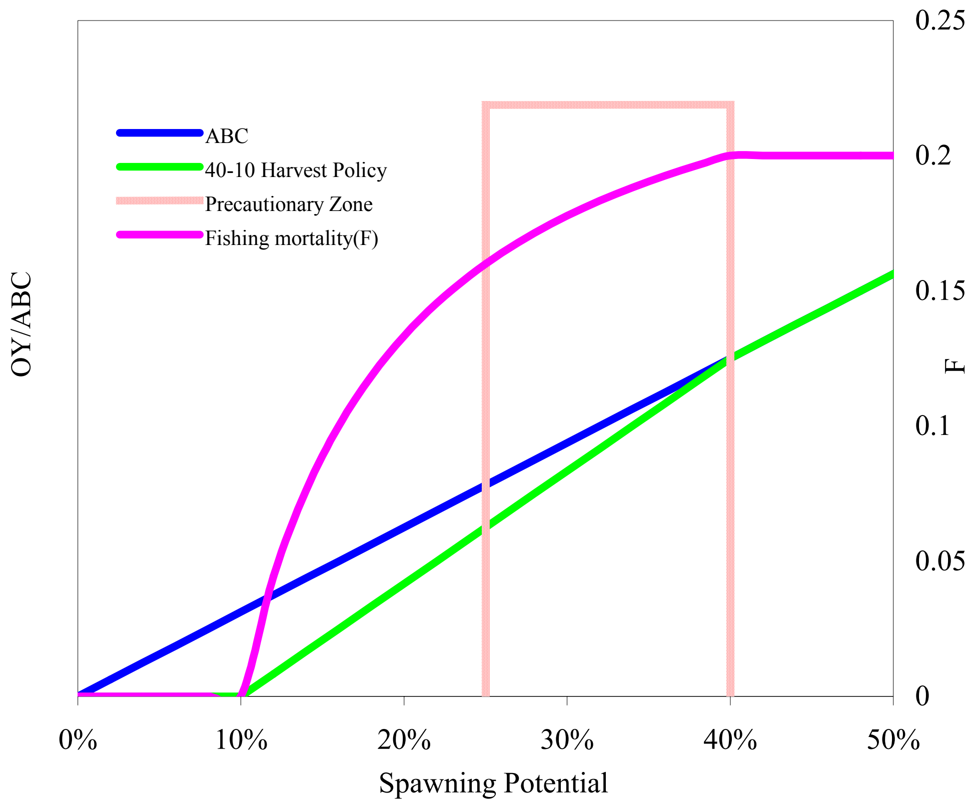


Figure 4.3. The '40-10' rule[23].

[23] Dr.Richard Methot (NMFS/NOAA, pers. commn.)

Chapter 5: Results and discussion

5.1 Catch

Figure 5.1 shows the average annual catch for the shore-based fishery versus the standard deviation of the annual average catch for this fishery for 110 variants of “Fraction/Minimum biomass” harvest strategy and the 40-10 rule. Figure 5.2 shows the same information as Figure 5.1, except that the results pertain to the whole fishery rather than just the shore-based fishery. Each line in Figures 5.1 and 5.2 represents a specific choice for the minimum biomass when applying the “Fraction/Minimum biomass” harvest strategy and a range for the fraction (Fr) removed given that the 3+ biomass exceeds the minimum biomass. Considering a single line, the value of Fr increases from the lowest value considered (Fr=0.05) corresponding to a point close to the x-axis to the largest fraction consisted (Fr=1). As expected, the catch by the shore-based fishery and the total catch (all sectors) decreases as the minimum biomass is increased from 0.4 B_0 to 0.9 B_0. Also, as expected, the standard deviation of the catch increases as the average catch increases. In contrast to the situation for minimum biomasses equal to or larger than 0.4 B_0, the average catch drops for high values for Fr when the minimum biomasses lies between 0.05 B_0 to 0.3 B_0 because of relative increased of non catch years to total catch.

The average annual catch by the shore-based fishery and total catch are both maximized when the minimum biomass is set to 0.05 B_0 and the catch is set to 20% of the difference between the 3+ biomass and 0.05 B_0 (the average annual catch by the shore-based fishery is 65,058 (MT) and that by the whole fishery is 282,654 (MT)). Stochastic dominance occurs when two harvest strategies have the same average catch but one has less variability. Harvest strategies that have a minimum biomass of 0.05 B_0 and values for Fr of 0.05, 0.1 and 0.2 exhibit stochastic dominance over harvest strategies that lead to the same average annual catch. While the '40-10' rule does not lead to the highest average annual catch for either the shore-based fishery or the whole fishery, it nevertheless performs at least as well as the "Fraction/Minimum biomass" strategy with a minimum biomass of 0.05 B_0 and a value for Fr between 0.1 and 0.2.

Figures 5.3 and 5.4 show respectively the distributions (aggregated over years and simulations (n=50 (years)*1000(simulations)) for the annual catch by the shore-based fishery and by the whole fishery, for harvest strategies with a minimum biomass of 0.05 B_0. The leftmost bin represents years in which the fishery was closed and the rightmost bin represents years in which the catch was constrained by the harvest capacity being reached. The fraction of years in which the fishery is closed is essentially zero for Fr values less than 0.2. However, this fraction increases rapidly with Fr once Fr exceeds 0.2.

There is a slight peak in the catch distribution at 600,000 MT in Figure 5.4 when Fr=0.6 and the size of this peak grows as Fr is increased. The exact reasons for this are unclear but may be related to the impact of occasional large recruitments. This is because large recruitments are harvested over several years when Fr is low but any increased biomass due to good recruitment is utilized rapidly when Fr is high.

Table 5.1 illustrates the non-catch risk (the percentage of years in which the fishery is closed). The non-catch risk exceeds 50% when the minimum biomass is $0.7B_0$ or larger. Only for minimum biomasses of 0.1 B_0 and lower does the non-catch risk never exceed 50% irrespective of the choice of Fr.

5.2 Net present value

Figure 5.5 shows the average net present value (see Equation 4.2.4) for the shore-based fishery versus the standard deviation of the net present value for this fishery for 110 variants of "Fraction/Minimum biomass" harvest strategy and the 40-10 rule. Figure 5.6 shows the same information as Figure 5.5, except that the results pertain to the whole fishery rather than just the shore-based fishery. As expected from Figures 5.1 and 5.2, there is a trade-off between average net present value and the variability of net present value.

Net present value for the shore-based fishery (Figure 5.5) exhibits "backwards bending" when Fr is between 0.2 and 0.3 for all choices for the minimum biomass. The "backwards bending" occurs because of the substantial negative benefits associated with fishery closure; this feature is not as evident in Figure 5.1 because fishery closure does not lead to a large negative impact on the average catch unlike the case for net present value. Several of the harvest strategies lead to negative net present value. The net present value of the shore-based fishery is maximized ($35,955,316) using the same strategy that maximized average catch (minimum biomass = $0.05B_0$; Fr=0.2). The '40-10' rule leads to only a slightly lower net present value than this best-performing harvest strategy (average and SD for NPV of $32,537,487 and $8,297,646 respectively).

The harvest strategy which has a minimum biomass of 0.2 B_0 and Fr=0.6 leads to the greatest net prevent on average ($1,253,900,000). Unlike the case for the shore-based fishery, there is no harvest strategy that clearly maximizes average net present value and minimizes the standard deviation of the net present value. The '40-10' rule again leads to a net present value that is between that for the Fr=1 / Fr=0.2, minimum biomass =0.05 B_0 harvest strategies.

5.3 Biomass

Figures 5.7 and 5.8 show distributions of 3+ biomass (Equation 3.1.4a) in the absence of fishing mortality. The average unfished biomass is 1,851,400 MT (SD 293,800 MT) if there are no occasional extreme recruitments (Figure 5.7). As expected, the average unfished biomass in absence of extreme recruitments is much lower than that when allowance is made for such recruitments (Figure 5.8). The distribution for unfished biomass is tight when there are no occasional extreme recruitments but this is not the case when there are occasional extreme recruitments. As expected, the standard deviation of the unfished biomass also increases with increasing values for the standard deviation of the size of an extreme recruitment when it occurs, σ_τ. The standard deviation of 3+ biomass increases from 1,792,200 MT for σ_τ=0.1 to 1,864,200 for MT for σ_τ=0.3 to 1,919,700 MT for σ_τ=0.5. In our simulation, only σ_τ=0.1 is applied.

Figure 5.9 shows average and standard deviation of 3+ biomass for various harvest strategies. The average biomass increases with increasing minimum biomass and decreasing Fr. There is again a trade-off between average biomass and the standard deviation of biomass. Figure 5.10 shows distributions of biomass for harvest strategies with a minimum biomass of 0.05 B_0. The distributions of biomass become tighter and the mean biomass gets lower as Fr is increased. Unlike the situation for catch, there is no evidence for a secondary peak at high biomass that can be attributed to occasional large recruitments.

5.4 Exploitation rate and biomass depletion

The harvest strategy that maximizes the average shore-based catch, shore-based net present value and total catch (minimum biomass=0.05 B_0 ;Fr =0.2) results in an average exploitation rate of 16.3 %, which is quite similar to the actual average exploitation rate between 1989 and 2001 (a time when the Pacific whiting fishery was Americanized and had expanded) of 16.4%. The maximum average exploitation rate in Table 5.2 is 25.5%, a substantially lower value than recent exploitation rates in the Pacific whiting fishery (33.1% in 2001).

Average catch decreases once Fr exceeds some critical level ("backwards bending"; Figures 5.1 and 5.2). "Backwards bending" occurs between Fr=0.2 and Fr=0.3 for minimum biomasses between 0.05 B_0 and 0.1 B_0 . Table 5.3 indicates that the average biomass depletion drops markedly between Fr=0.2 and Fr=0.3 (42% to 24% for 0.05 B_0 and 43% and 32% for 0.1 B_0) for these minimum biomasses. The lower average biomass levels correspond to more frequent fishery closures (Figures 5.3 and 5.4; Table 5.1) and also to lower productivity (*MSY* is achieved somewhere between 30 and 40% of B_0).

Table 5.4. indicates the minimum depletion rate in simulations for each harvest strategy. While Fr=0.1 and 0.2 with minimum biomass =0.05 B_0 is able to keep minimum depletion rate over 0.05 B_0 , over Fr=0.3 with minimum biomass =0.05 B_0 indicates minimum biomass less than 0.05 B_0 . Once management target is set as minimum biomass = 0.05 B_0 , the risk of biomass below 0.05 B_0 is low for small Fr's. In this sense, the harvest strategy with minimum biomass= 0.05 B_0 and Fr=0.2 performed well by keeping biomass over given minimum biomass level.

Figures 5.11-5.18 plot the average and standard deviation of the shore-based catch, the total catch, the shore-based net present value, and the total net present value against the average biomass depletion. For a given minimum biomass, the biomass depletion decreases as Fr is increased due to the impact of higher fishing mortality rates. Average shore-based catch, average total catch, average shore-based net present value and average total net present value are maximized at about 40% of the unfished level, i.e. 0.4 B_0 (Figures 5.11, 5.13, 5.15 and 5.17). This explains why the '40-10' rule performed reasonably adequately in this study. Although the average shore-based net present value for harvest strategies with minimum biomasses of 0.05 B_0, 0.1 B_0 and 0.2 B_0 change as a function of average biomass depletion and a clear maximum point is evident, this is not the case for the standard deviation of the net present value which is almost independent of the biomass depletion (Figure 5.16). Therefore, when selecting an appropriate harvest strategy for the shore-based fishery, it is only necessary to consider the trade-off between the average shore-based net present value and the average biomass depletion (Figure 5.15).

5.5 Discussion

This study examined the magnitude of the trade-off between the average catch and its variability as well as that between the average economic return (net present value) and its variability across a range of harvest strategies. The primary objective of this study was to identify a harvest strategy that minimized the variability in catches and net present value yet nevertheless still achieved a reasonable average outcome.

A number of general trends in the mean-variance relationship were evident. The variance in the shore-based catch, the total catch, the shore-based net present value, the total net present value and biomass increased as the mean increased.

However, the relationship between the mean and variance was not linear. In particular, for several types of harvest strategy, as the fraction increased the average catch begins to decrease due to biomass depletion.

Except for average biomass, harvest strategies with a minimum biomass of $0.05\,B_0$ always stochastically dominated some other harvest strategy. A conclusion of this study is therefore that harvest strategies which have a low minimum biomass and a low harvest rate when the biomass exceeds the minimum biomass are desirable because they maximize average behavior and have relatively lower variance than strategies with high minimum biomasses. Specifically, a strategy with a minimum biomass of $0.05B_0$ and which sets the catch limit to 20% of the 3+ biomass in excess of this level is highly desirable as it maximizes the average total catch and the average net present value yet does not result in highly variable outcomes. A particularly desirable outcome of this harvest strategy is that the non-catch risk is essentially zero, which virtually guarantees that some fishing will occur in all years.

In principle[24], the '40-10' rule currently used to manage the Pacific whiting fishery closes the fishery at $0.1\,B_0$ and this rule is therefore similar to the "Fraction/Minimum biomass" strategy with a minimum biomass of $0.1B_0$. Harvest strategies with a minimum biomass of $0.05\,B_0$ and low values for Fr (0.05-0.2) preformed better than those with a minimum biomass of $0.1\,B_0$ in the simulations of this study. In particular, the harvest strategy with a minimum biomass of $0.05B_0$ and an Fr of 0.2 kept the average biomass substantially above $0.05B_0$ at $0.42B_0$ (Table 5.3).

[24] In principle, because if a stock drops below $0.25B_0$, it is necessary to develop a rebuilding plan. The rebuilding plan will probably allow some harvesting at population levels below $0.1B_0$.

The 40-10 rule is based on the assumption that Maximum Sustainable Yield (MSY) is achieved at 40% of the unfished spawning output. Although 3+ biomass is not identical to spawning biomass, the results of this study which found that maximum catch was achieved when the biomass was on average at $0.42B_0$ suggest that this assumption is probably not violated to a substantial extent.

There are two limitations of this study. One is that variability in the annual migration pattern is not included in the bio-economic model. This is a major factor because it impacts the availability of fish to some of the fishing sectors and could lead to actual catches being well below the TAC. Another limitation of this study is that no information was available on the desirable trade-off between average outcomes and the variability of these outcomes, i.e. how much yield should be sacrificed to reduce variability. Therefore, although this study could illustrate the opportunities of between average and variance, we did not identify the particular trade-off that is desirable to managers and industry. Future work conducted in collaboration with industry and the managers could better identify those strategies that are of greatest interest.

Table 5.1. The non-catch risk (the percentage of years in which the fishery is closed) for the 110 "Fraction/Minimum biomass" harvest strategies and 40-10 harvest strategy has 0.37%

	Fr=0.05	Fr=0.1	Fr=0.2	Fr=0.3	Fr=0.4	Fr=0.5	Fr=0.6	Fr=0.7	Fr=0.8	Fr=0.9	Fr=1
0.9Bzero	63.18%	65.82%	70.37%	74.12%	76.65%	78.19%	80.05%	80.84%	81.62%	82.24%	82.73%
0.8Bzero	58.44%	62.21%	66.27%	70.68%	73.56%	75.45%	77.53%	78.49%	79.90%	80.60%	80.81%
0.7Bzero	53.25%	56.50%	61.90%	66.01%	69.29%	72.19%	74.01%	75.80%	76.67%	77.57%	78.53%
0.6Bzero	44.94%	50.84%	54.24%	60.31%	64.06%	65.90%	69.48%	70.40%	73.40%	74.55%	74.02%
0.5Bzero	35.59%	39.07%	45.44%	50.33%	54.72%	58.30%	61.25%	63.71%	65.67%	67.32%	68.57%
0.4Bzero	20.99%	24.21%	31.21%	36.95%	41.69%	45.91%	49.57%	52.80%	56.06%	58.70%	59.81%
0.3Bzero	7.96%	11.25%	17.05%	21.58%	26.81%	34.10%	35.96%	44.68%	46.13%	49.40%	57.22%
0.2Bzero	1.92%	2.69%	5.57%	9.19%	14.09%	22.49%	24.85%	36.08%	39.63%	44.08%	50.18%
0.1Bzero	0.01%	0.04%	0.21%	1.85%	6.19%	9.52%	18.52%	20.79%	36.23%	40.91%	34.33%
0.05Bzero	0.00%	0.00%	0.00%	1.97%	6.35%	4.00%	16.88%	15.87%	28.53%	33.52%	31.73%

Table 5.2. The average exploitation rate for 110 “Fraction/Minimum biomass” harvest strategies, and 40-10harvest strategy has 11.68%. The maximum average exploitation rate is 25.46%(minimum biomass=0.05 $\boldsymbol{B_0}$ and fraction=0.5).

Fraction	0.05	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0.9Bzero	0.6%	1.0%	1.6%	2.0%	2.2%	2.5%	2.6%	2.8%	2.9%	3.0%	3.1%
0.8Bzero	0.7%	1.2%	2.0%	2.4%	2.7%	3.0%	3.1%	3.3%	3.4%	3.5%	3.6%
0.7Bzero	0.9%	1.6%	2.4%	3.0%	3.4%	3.6%	3.8%	3.9%	4.1%	4.2%	4.3%
0.6Bzero	1.1%	1.9%	3.1%	3.7%	4.1%	4.6%	4.7%	5.0%	4.9%	5.0%	5.4%
0.5Bzero	1.4%	2.4%	3.8%	4.8%	5.4%	5.7%	6.0%	6.2%	6.3%	6.5%	6.6%
0.4Bzero	1.8%	3.2%	5.1%	6.3%	7.1%	7.5%	8.0%	8.1%	8.4%	8.6%	8.7%
0.3Bzero	2.4%	4.2%	6.9%	8.7%	9.8%	10.1%	10.9%	10.5%	11.0%	11.2%	10.4%
0.2Bzero	3.1%	5.6%	9.5%	11.9%	13.3%	13.2%	14.5%	13.3%	13.8%	13.8%	13.2%
0.1Bzero	4.0%	7.5%	13.3%	16.4%	17.8%	19.1%	18.4%	19.7%	16.2%	16.3%	20.3%
0.05Bzero	4.5%	8.7%	16.3%	19.0%	20.6%	25.5%	21.7%	24.3%	20.8%	20.8%	23.2%

Table 5.3. Average biomass depletion for 110 “Fraction/Minimum biomass” harvest strategies, and 40-10 harvest strategy has 51.88%.

Fraction	0.05	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0.9Bzero	84%	81%	76%	72%	70%	69%	68%	67%	67%	67%	66%
0.8Bzero	83%	78%	74%	70%	68%	67%	65%	65%	63%	63%	63%
0.7Bzero	81%	77%	70%	67%	65%	63%	62%	61%	61%	60%	59%
0.6Bzero	81%	74%	69%	64%	61%	60%	58%	58%	57%	56%	56%
0.5Bzero	79%	73%	65%	60%	58%	56%	55%	54%	53%	52%	52%
0.4Bzero	77%	71%	61%	56%	53%	51%	50%	48%	48%	47%	46%
0.3Bzero	77%	67%	56%	51%	47%	44%	44%	40%	40%	40%	36%
0.2Bzero	75%	63%	51%	44%	39%	34%	34%	30%	29%	28%	27%
0.1Bzero	71%	59%	43%	32%	26%	23%	20%	19%	15%	15%	17%
0.05Bzero	70%	57%	42%	24%	18%	17%	13%	12%	10%	10%	10%

Table 5.4. Minimum biomass depletion in simulations for 110 “Fraction/Minimum biomass” harvest strategies.

Fraction	0.05	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0.9Bzero	15.4%	15.4%	15.4%	16.6%	16.6%	15.4%	16.6%	15.4%	15.3%	15.3%	15.4%
0.8Bzero	13.7%	15.2%	13.7%	15.6%	15.6%	13.7%	15.6%	13.7%	15.2%	15.2%	13.7%
0.7Bzero	13.6%	11.5%	13.4%	15.4%	15.4%	13.3%	15.4%	13.3%	11.4%	11.4%	13.2%
0.6Bzero	16.5%	15.4%	16.5%	16.3%	16.0%	15.9%	15.8%	15.1%	14.8%	14.7%	15.1%
0.5Bzero	15.0%	14.9%	14.5%	14.3%	14.2%	14.3%	14.2%	14.3%	14.3%	14.3%	14.2%
0.4Bzero	13.6%	14.5%	13.4%	13.3%	13.3%	12.4%	13.2%	11.9%	13.9%	13.3%	11.4%
0.3Bzero	15.4%	15.1%	13.7%	15.3%	14.9%	11.8%	14.2%	10.9%	10.7%	10.6%	9.4%
0.2Bzero	13.6%	14.9%	11.3%	11.7%	11.0%	9.7%	9.8%	9.2%	6.9%	6.3%	7.6%
0.1Bzero	13.3%	9.7%	8.4%	7.2%	6.3%	6.2%	5.7%	4.6%	4.2%	4.1%	3.5%
0.05Bzero	9.6%	8.9%	5.3%	3.1%	2.7%	3.1%	2.4%	2.6%	2.3%	2.0%	1.9%

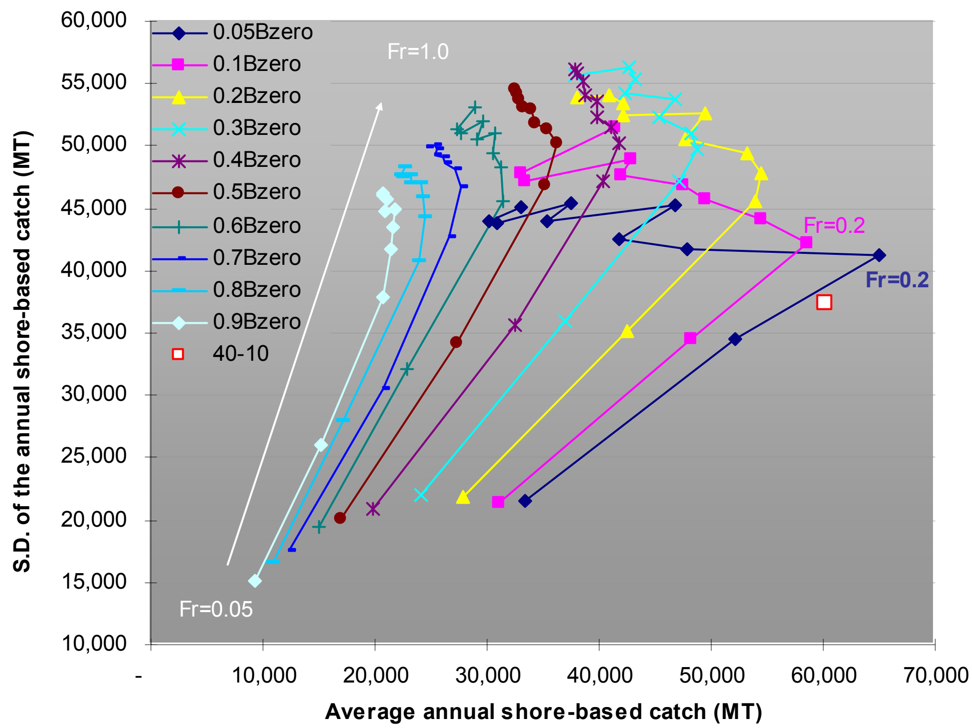


Figure 5.1. Average and standard deviation of the annual catch by the shore-based fishery for 110 variants of the "Fraction/Minimum biomass" harvest strategy and the 40-10 rule.

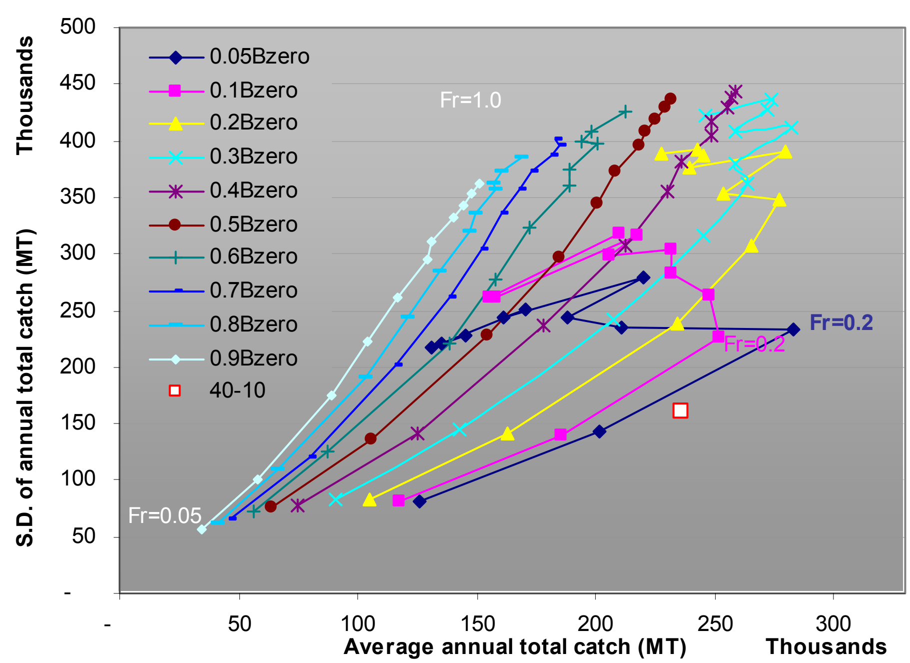
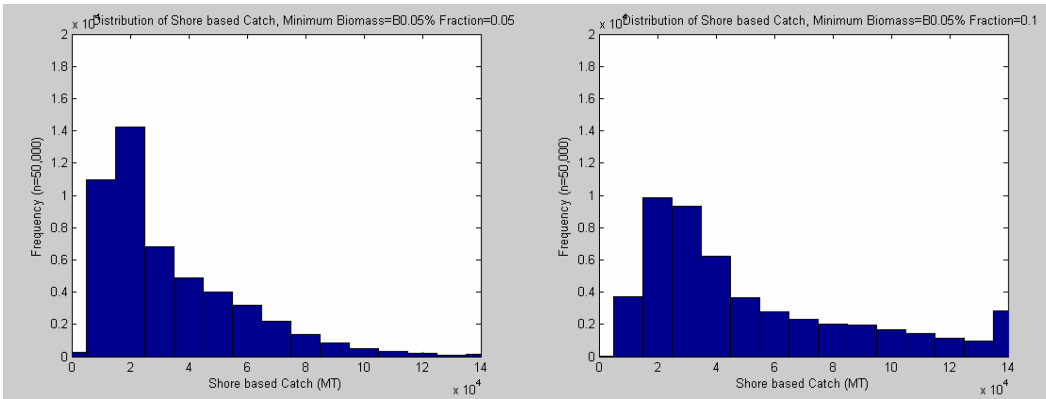
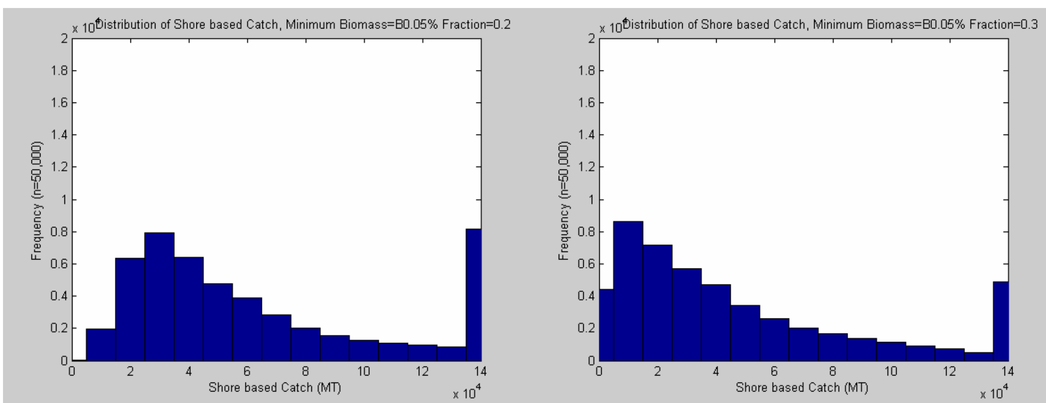


Figure 5.2. Average and standard deviation of annual total catch.

Fraction=0.05 Fraction=0.1



Fraction=0.2 Fraction=0.3



Fraction=0.4 Fraction=0.5

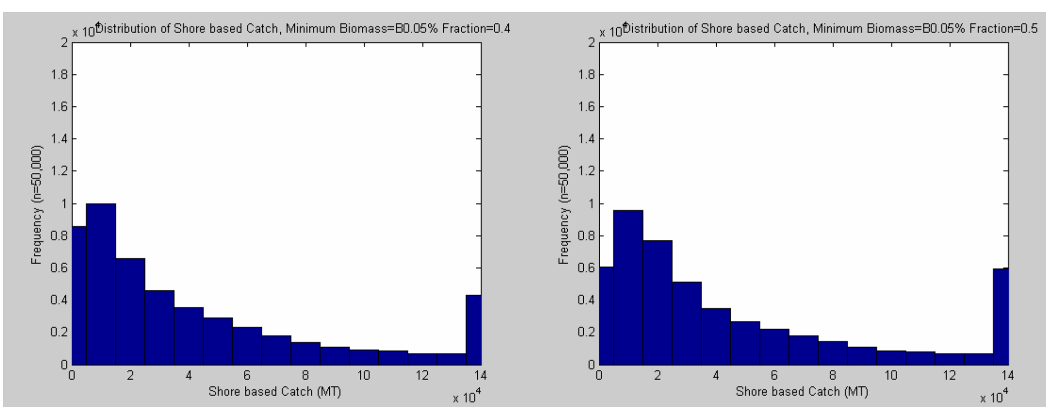
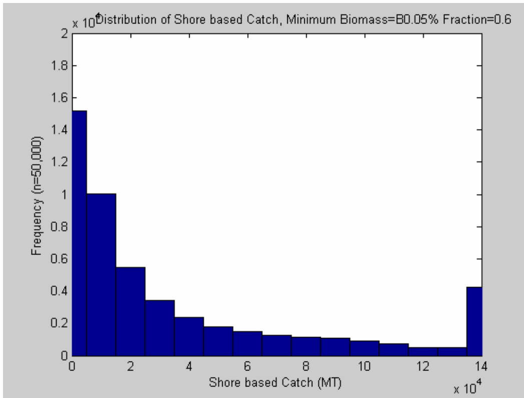


Figure 5.3. Distribution of the annual catch by the shore-based fishery for harvest strategies with a minimum biomass of 0.05 B_0 .

Fraction=0.6



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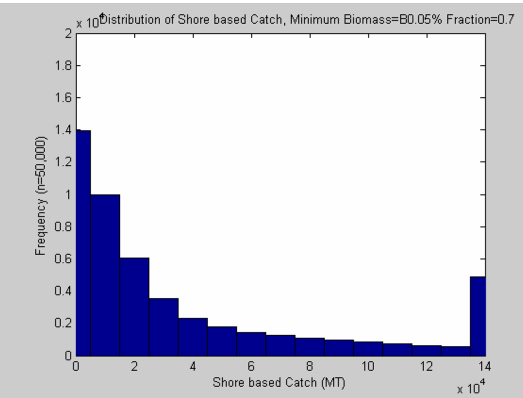

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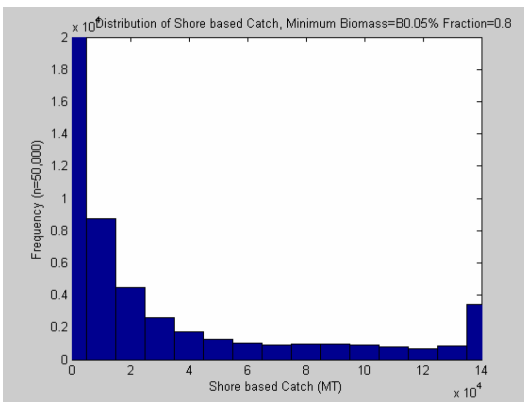

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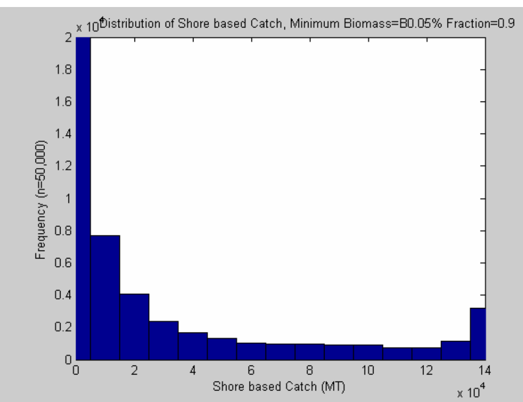

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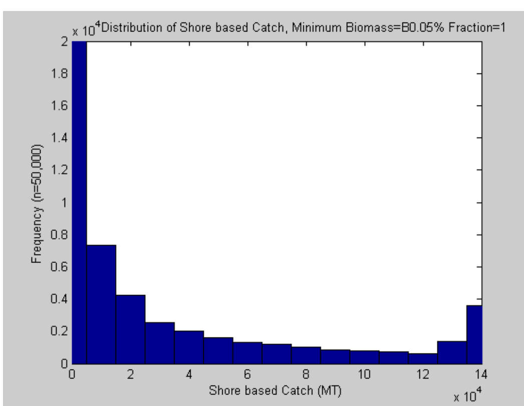

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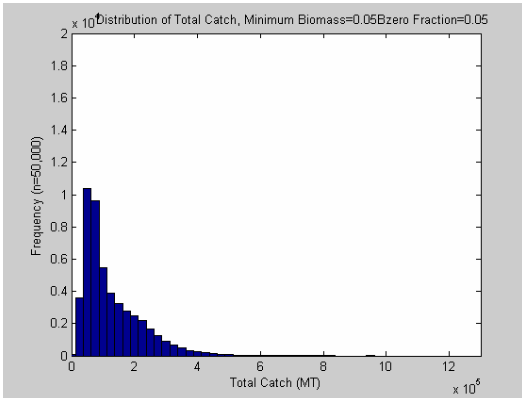

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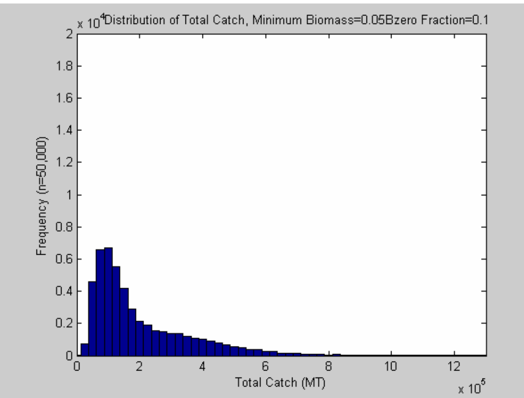

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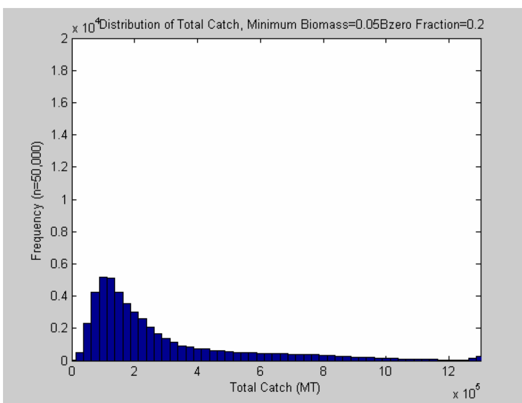

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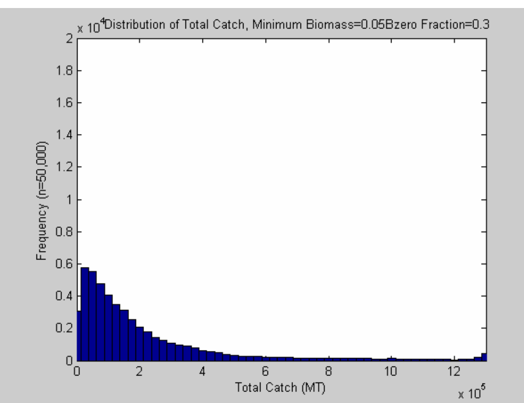

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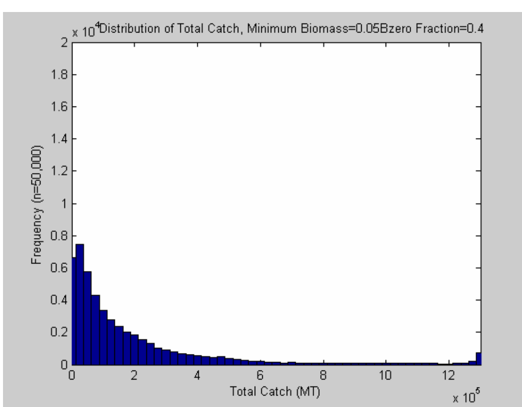

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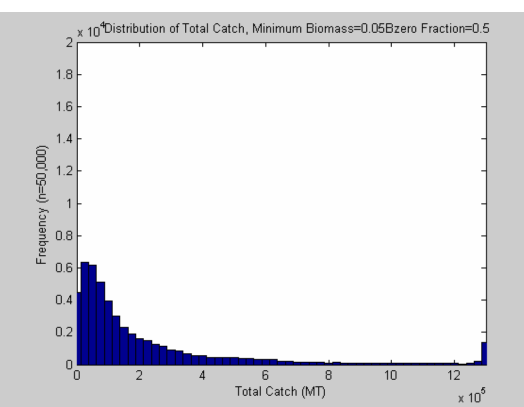

Figure 5.4.Distribution of the annual catch by the whole fishery for harvest strategies with a minimum biomass of 0.05 B_0.

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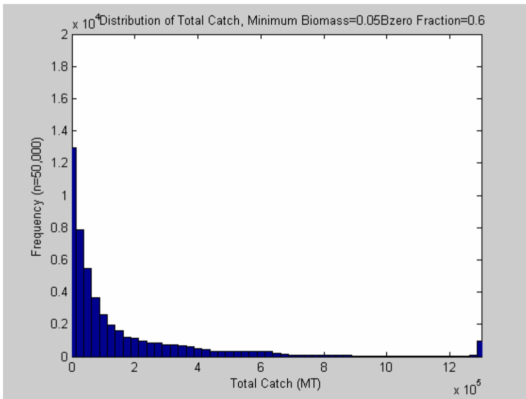

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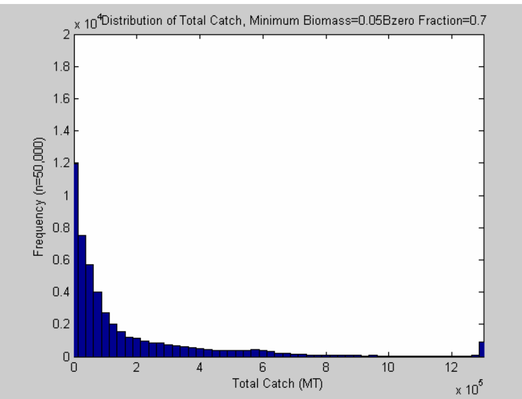

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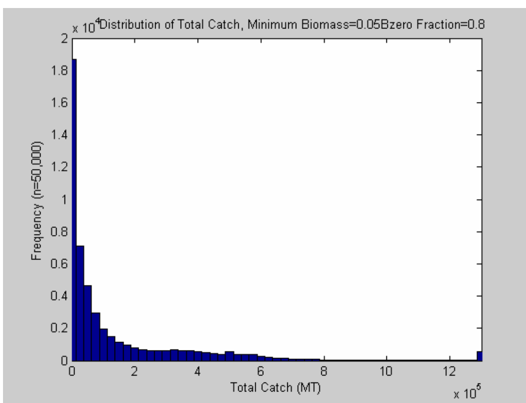

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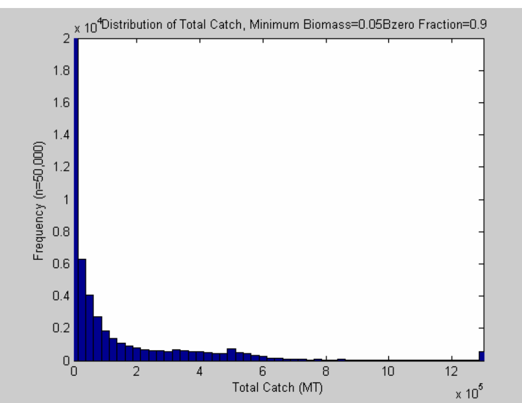

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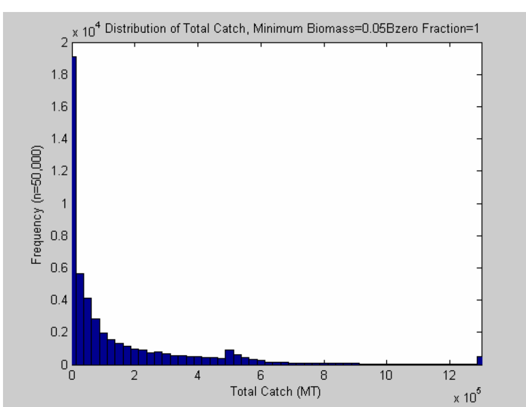

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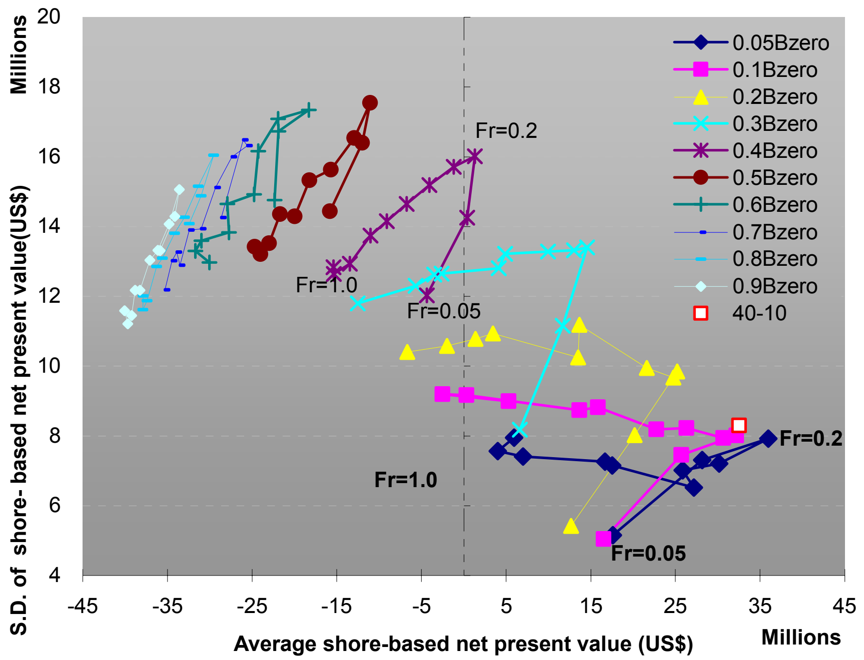

Figure 5.5. Average and standard deviation of the net present for the shore-based fishery.

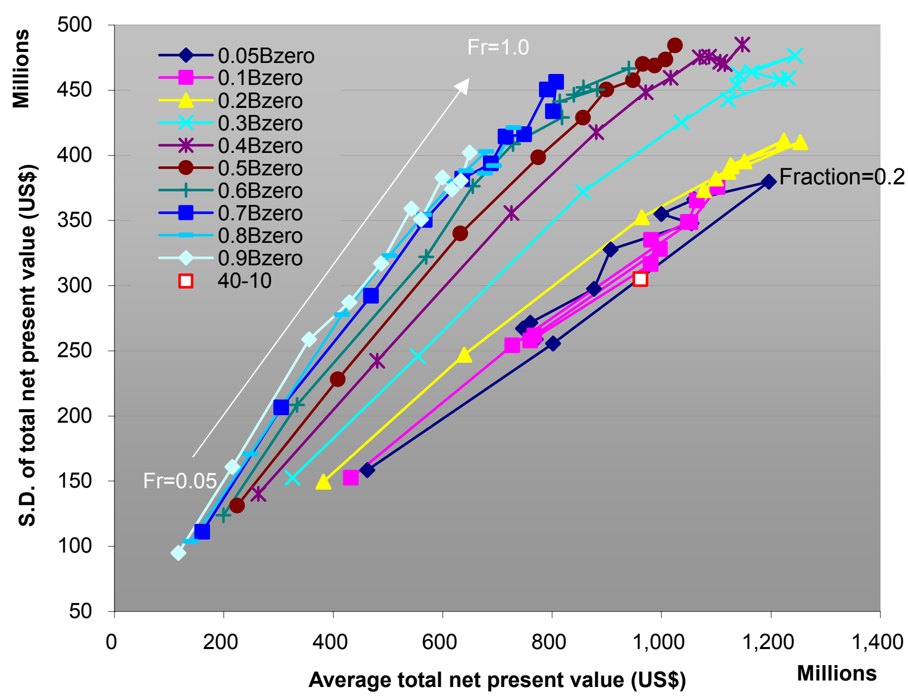

Figure 5.6. Average and standard deviation of the net present value for the whole fishery.

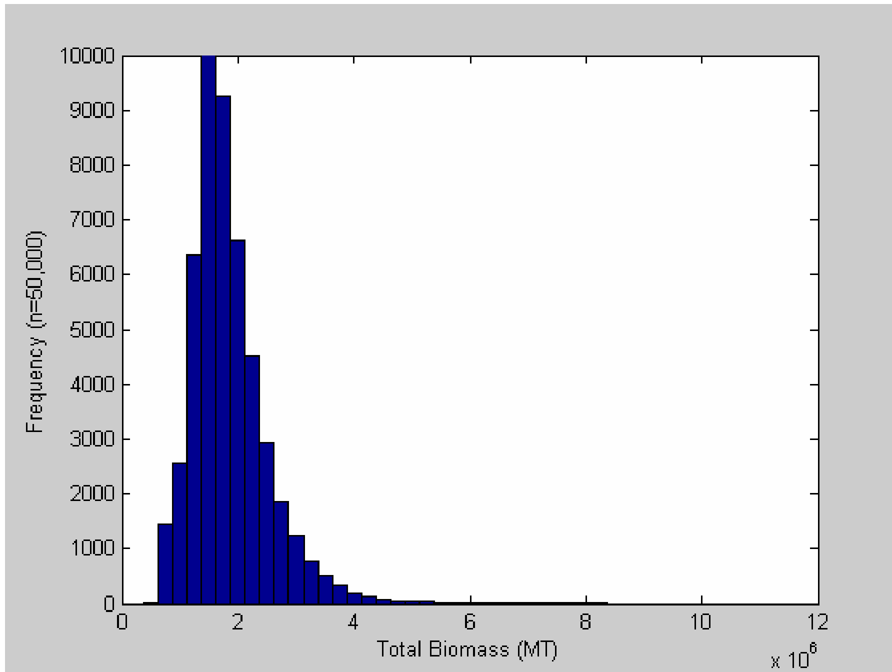

Figure 5.7. Distribution of biomass without fishing mortality and occasional extremely large recruitments.

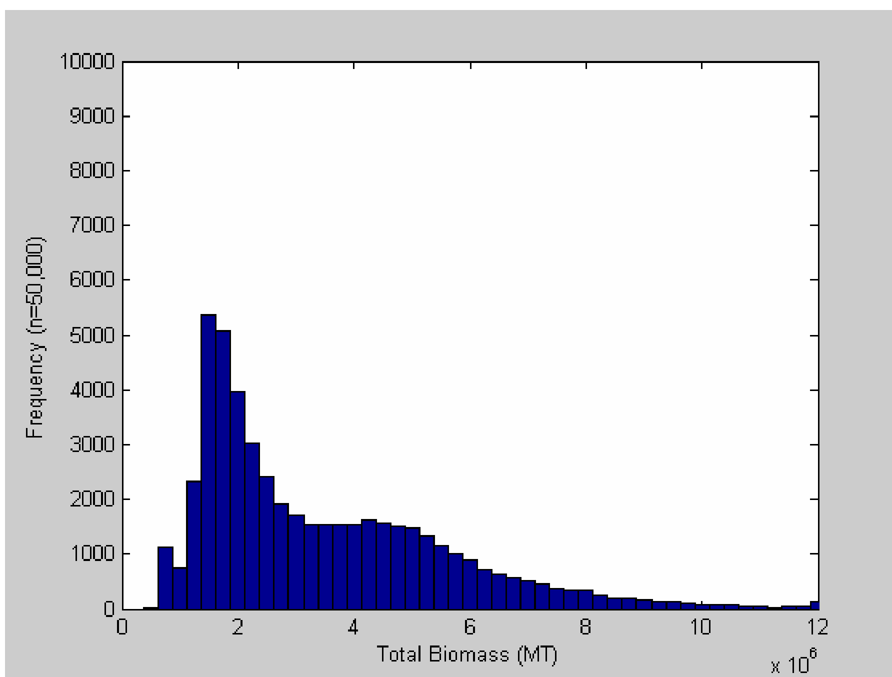

Figure 5.8. Distribution of biomass without fishing mortality (σ_τ =0.1).

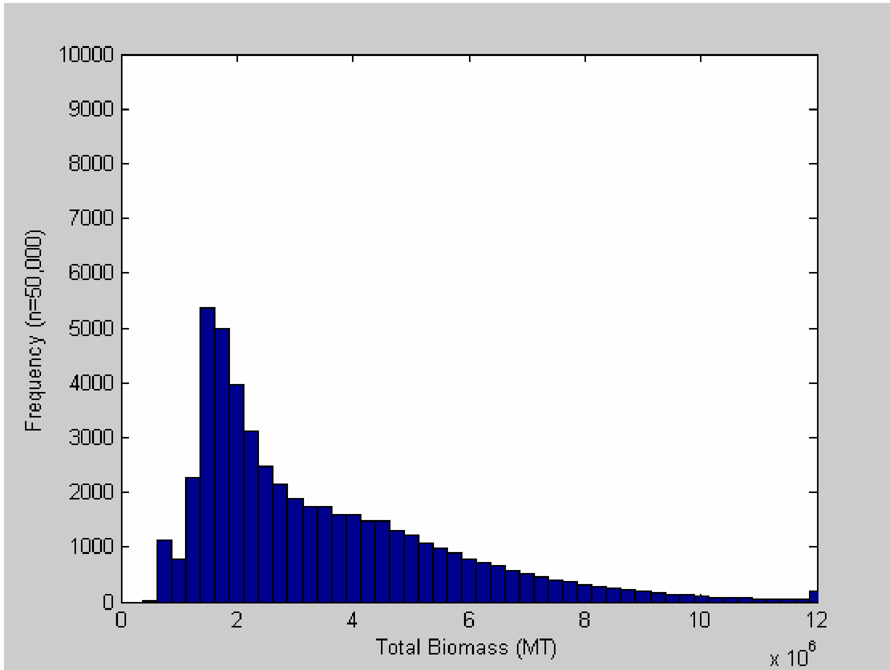

Figure 5.9. Distribution of biomass without fishing mortality (σ_τ =0.3).

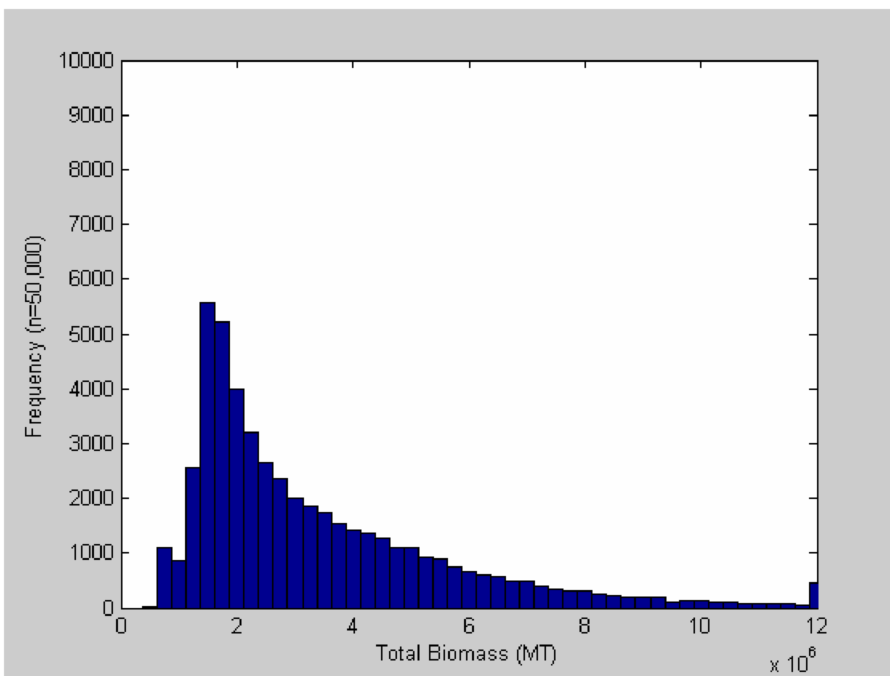

Figure 5.10. Distribution of biomass without fishing mortality (σ_τ =0.5).

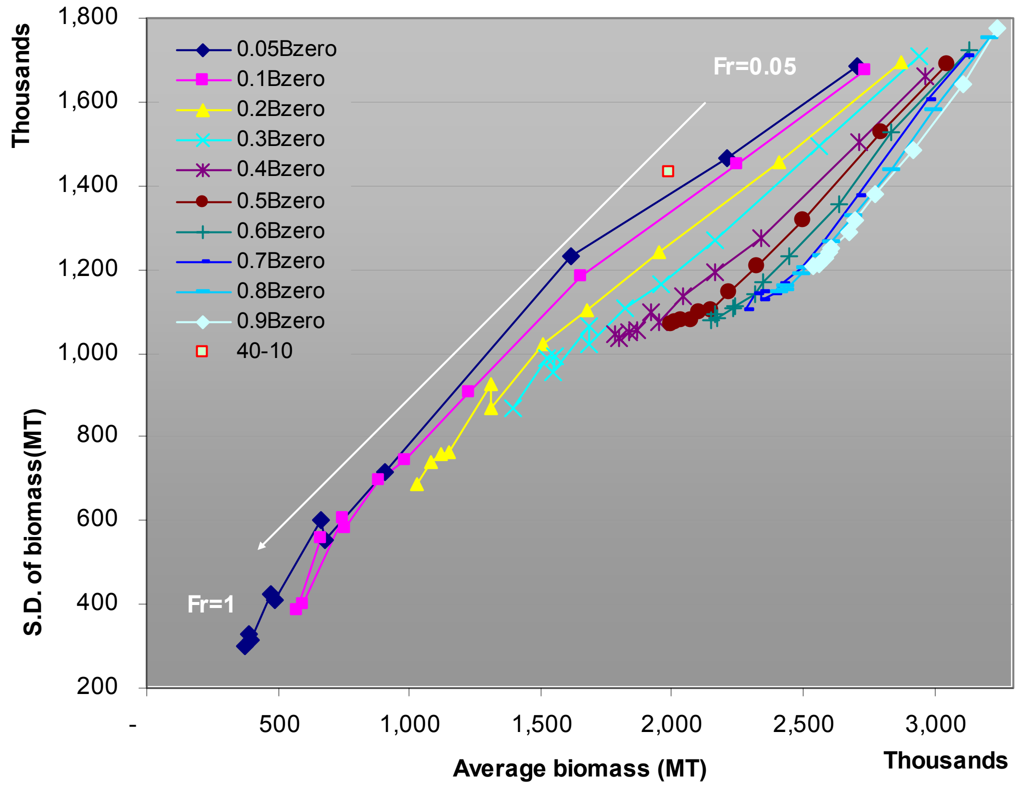

Figure 5.11. Average and standard deviation of biomass (MT)

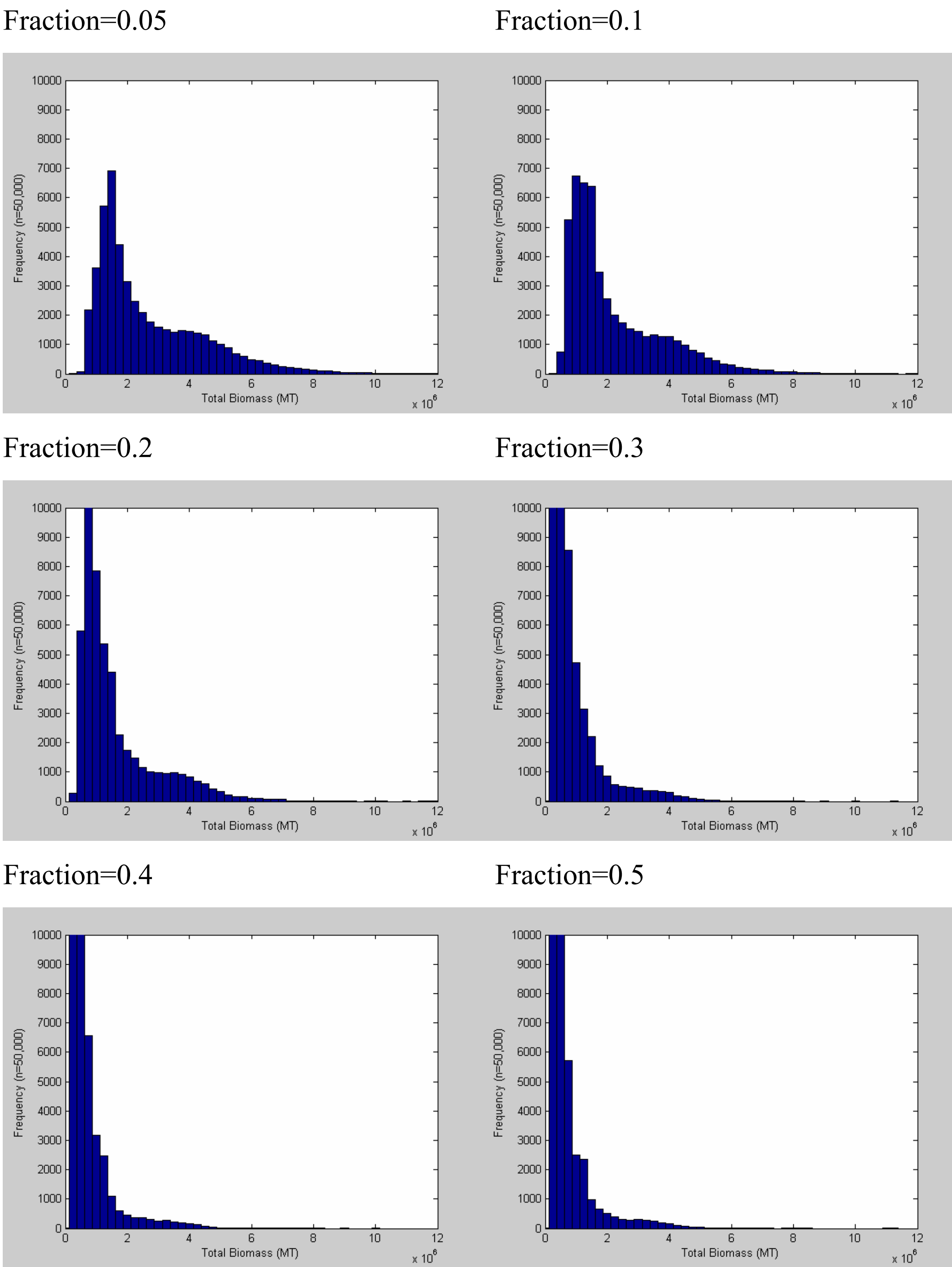

Figure 5.12. Distribution of biomass (Minimum biomass=0.05 B_0)

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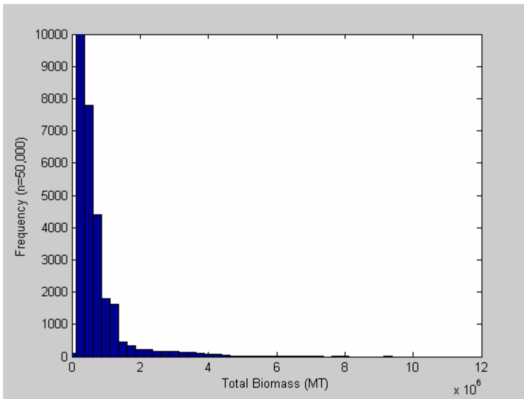

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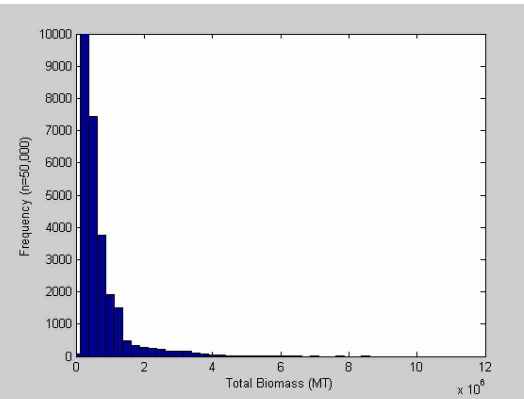

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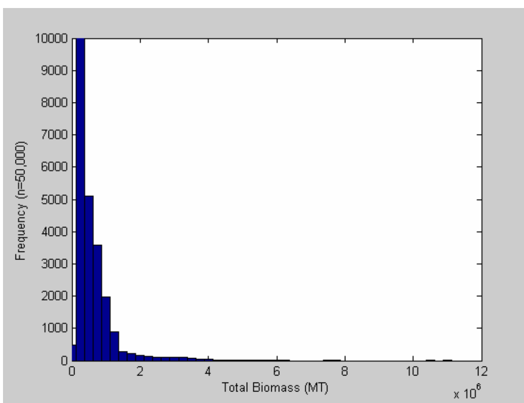

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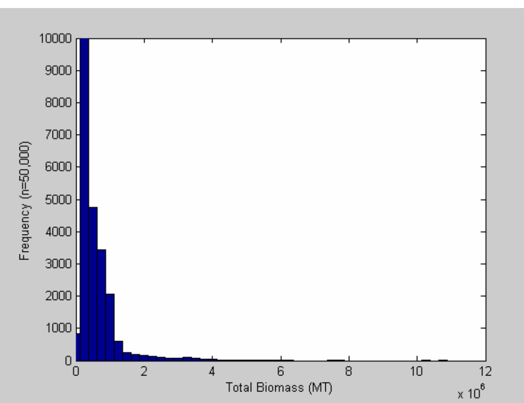

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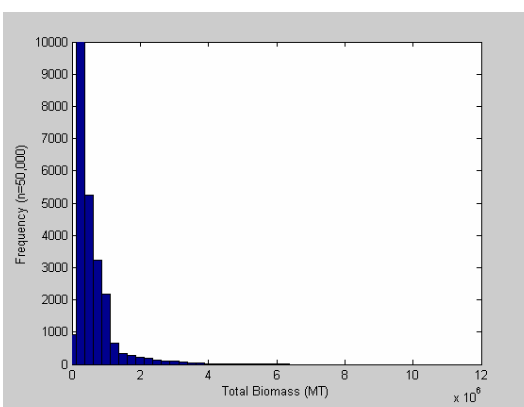

Figure 5.12. continued

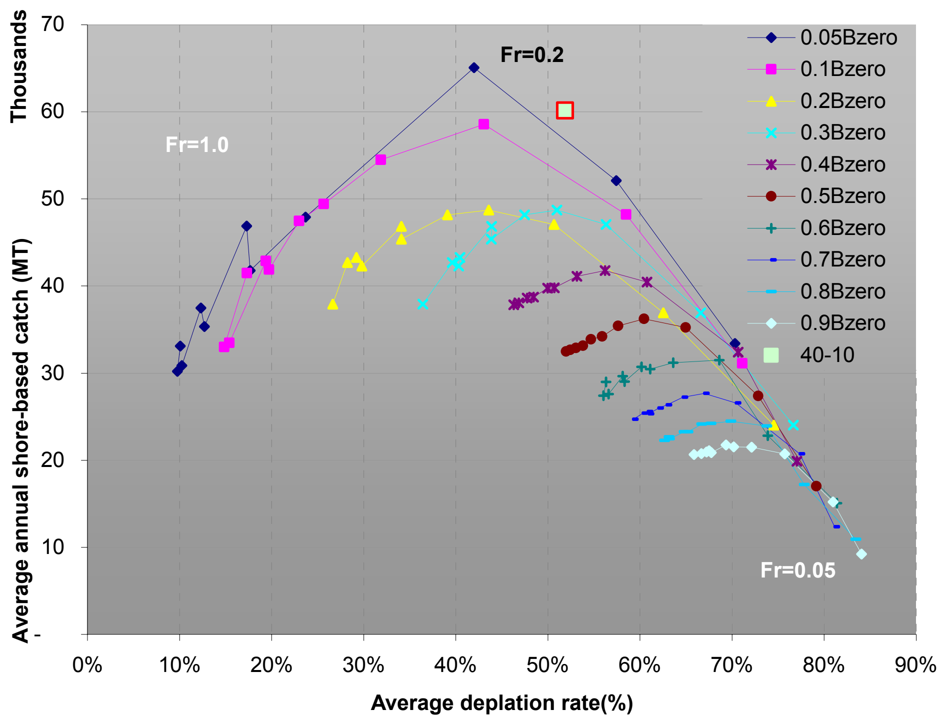

Figure 5.13. Average annual shore-based catch *versus* average biomass depletion.

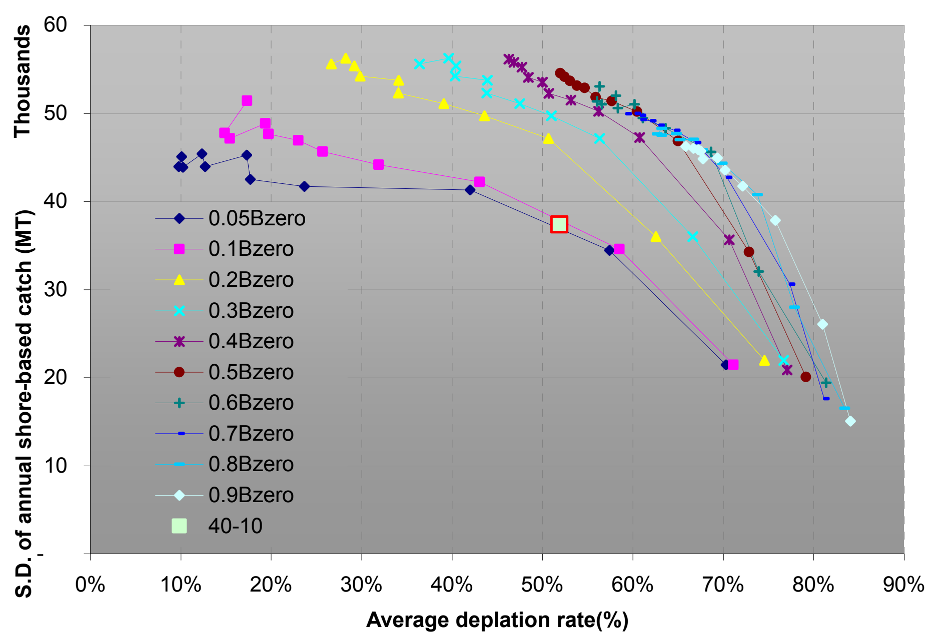

Figure 5.14. Standard deviation of the annual shore-based catch versus average biomass depletion.

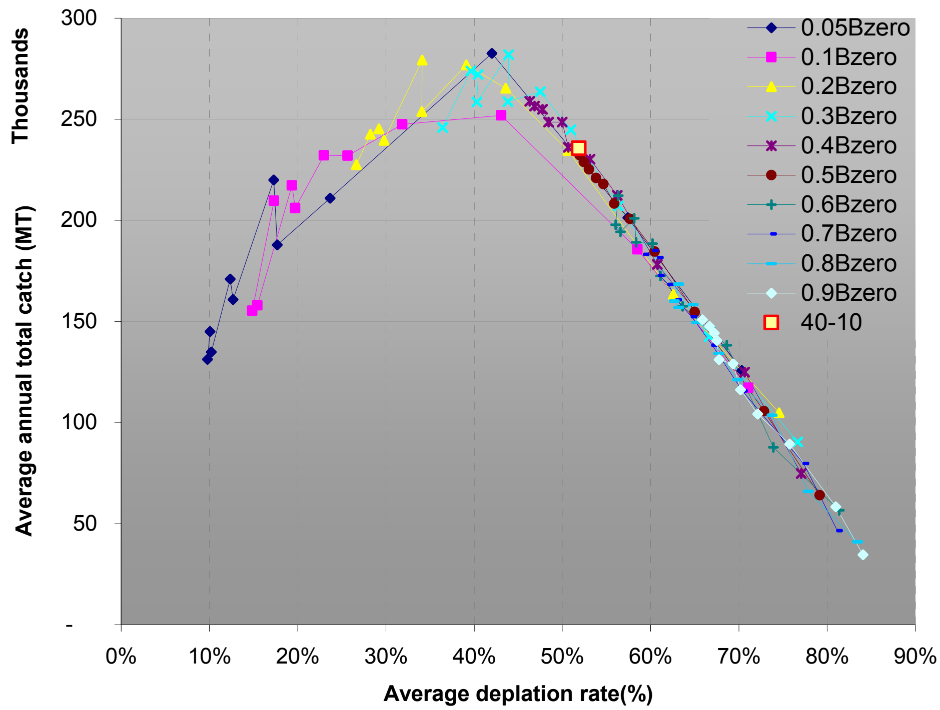

Figure 5.15. Average annual total catch *versus* average biomass depletion.

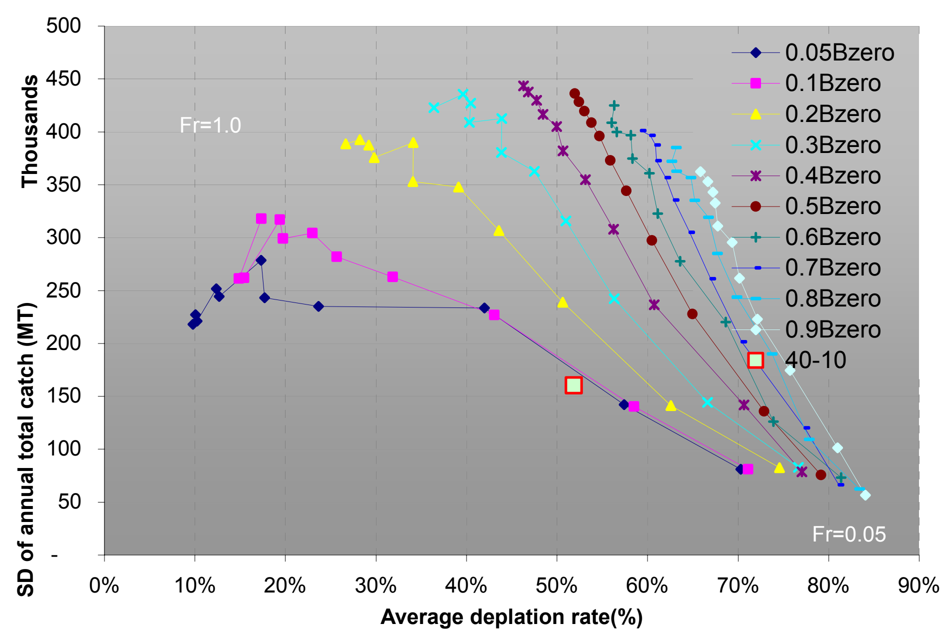

Figure 5.16. Standard deviation of the annual total catch versus average biomass depletion.

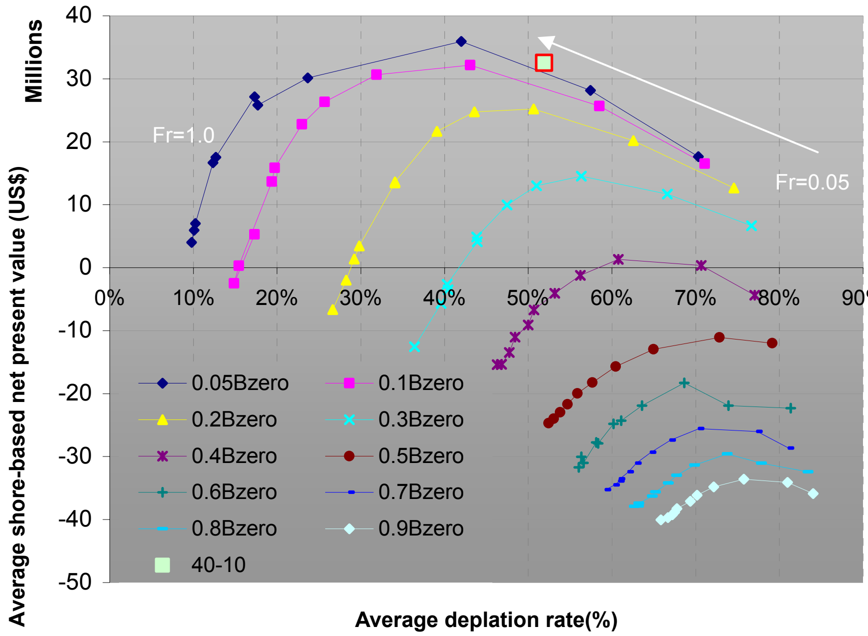

Figure 5.17. Average net present value for the shore-based fishery *versus* average biomass depletion.

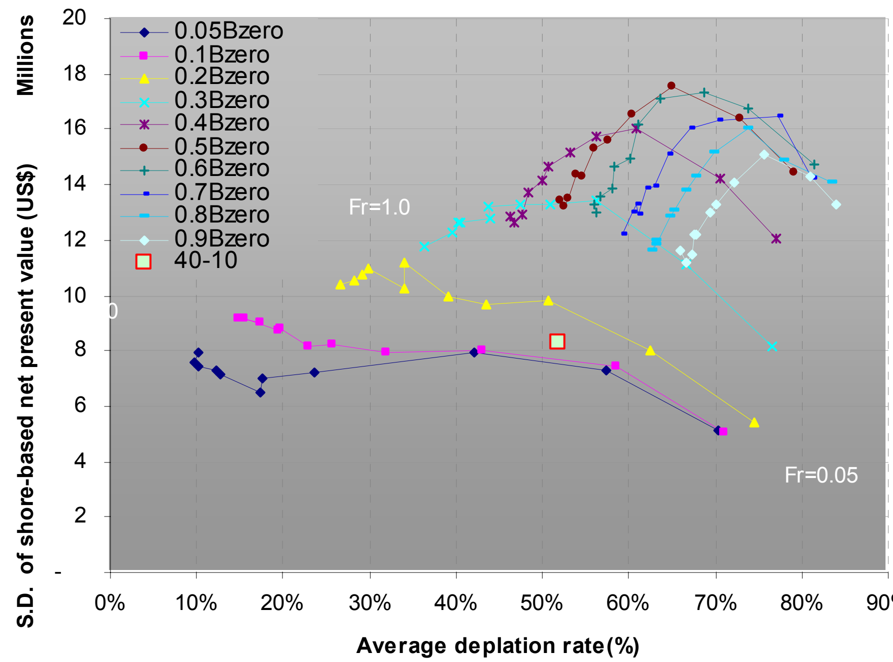

Figure 5.18. Standard deviation of the average net present value for the shore-based fishery *versus* average biomass depletion.

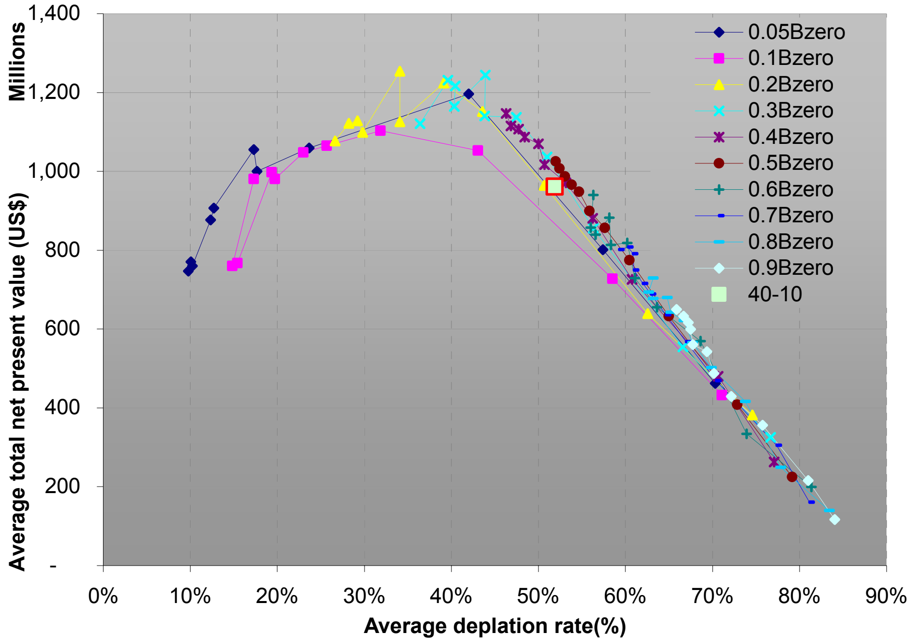

Figure 5.19. Average net present value for the whole fishery *versus* average biomass depletion.

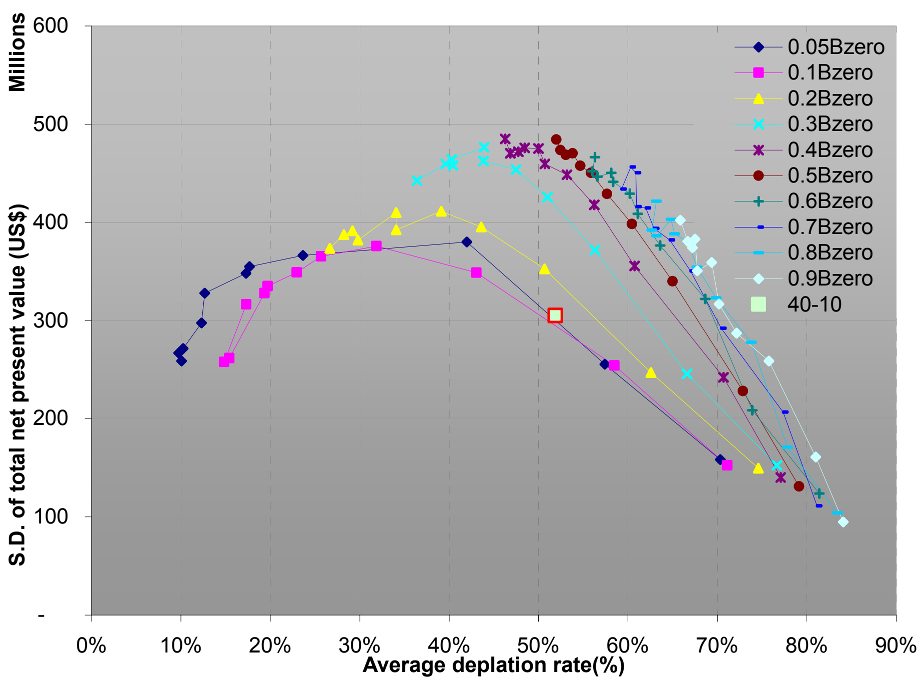

Figure 5.20. Standard deviation of the average net present value for the whole fishery *versus* average biomass depletion.

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Appendix 1: Key inputs for model

Population dynamics and SR model	
initial number of fish	Assessment conducted by Helser *et al*. (2002)
natural mortality	Assessment conducted by Helser *et al*. (2002)
weight at age (population)	Assessment conducted by Helser *et al*. (2002)
weight at age (US)	Assessment conducted by Helser *et al*. (2002)
weight at age (Canada)	Assessment conducted by Helser *et al*. (2002)
female mutuality	Assessment conducted by Helser *et al*. (2002)
female weight multiplier	Assessment conducted by Helser *et al*. (2002)
fishing selectivity	Assessment conducted by Helser *et al*. (2002)
SR data (1972-2001)	Assessment conducted by Helser *et al*. (2002)

Economic model	
sector capacity	Estimated from PFMC 1996 and Greer 2002

Harvest economic model	
catch capacity per a catcher boat	Estimated from PACFIN data (2001)
ex vessel price	Estimated from PACFIN data (2001)
operational oost	Estimated in this study

Harvest/Processor aggregated model	
net economic benefit	From Freese et al., 1996

Appendix 2: Sensitivity of variance for error in occasional extremely large recruitments (σ_τ)

In the simulation, the variance for error in occasional extremely large recruitments (σ_τ) is assumed as 0.1. Table A2.1 shows the distribution of recruitments which were generated by constant spawning stock biomass (SSB=1.3627 million MT, historical average 1971-2001), R^*=0.7609 and S^*=0.5601) for parameters of the Hockey stick model (fitted to historical recruitments from the maximum likelihood estimate (MLE) from Helser *et al.*). Although the number of samples in the sensitivity test is far greater than in the historical data (n=24,500 for sensitivity test and n=28 for historical maximum posterior density estimates), σ_τ=0.1 results in similar distribution of historical recruitment occurrences from MPD estimates while adding errors into occasional extremely large recruitment.

Table A2.1. Distribution of recruitments for alternative σ_τ (n=24500) and historical recruitments (n=28) based on the maximum likelihood estimation from Helser *et al* (2002).

σ_τ	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**	**MLE**
	Recruitments (billion fish)										
0-2	**79.25%**	79.36%	79.44%	79.53%	79.86%	80.16%	80.90%	81.26%	82.03%	82.99%	**82.14%**
2-4	**12.58%**	12.49%	12.43%	12.41%	12.43%	12.44%	12.20%	12.17%	11.86%	11.32%	**10.71%**
4-6	**0.71%**	0.79%	1.17%	1.56%	1.86%	1.95%	1.93%	1.94%	1.92%	1.80%	**0.00%**
6-8	**0.58%**	1.33%	1.64%	1.68%	1.57%	1.44%	1.28%	1.23%	1.08%	1.00%	**0.00%**
8-10	**3.02%**	2.42%	1.97%	1.59%	1.32%	1.13%	0.97%	0.83%	0.69%	0.62%	**3.57%**
10-15	**3.83%**	3.33%	2.71%	2.26%	1.86%	1.61%	1.41%	1.18%	1.05%	0.97%	**3.57%**
15-20	**0.03%**	0.28%	0.55%	0.69%	0.68%	0.70%	0.63%	0.60%	0.53%	0.48%	**0.00%**
20-25	**0.00%**	0.01%	0.08%	0.21%	0.27%	0.31%	0.31%	0.32%	0.30%	0.29%	**0.00%**
25-30	**0.00%**	0.00%	0.01%	0.04%	0.09%	0.13%	0.16%	0.17%	0.18%	0.17%	**0.00%**
30-35	**0.00%**	0.00%	0.00%	0.01%	0.04%	0.06%	0.09%	0.10%	0.11%	0.10%	**0.00%**
35-40	**0.00%**	0.00%	0.00%	0.01%	0.02%	0.03%	0.05%	0.06%	0.07%	0.08%	**0.00%**
40-45	**0.00%**	0.00%	0.00%	0.00%	0.01%	0.02%	0.03%	0.04%	0.04%	0.05%	**0.00%**
45-50	**0.00%**	0.00%	0.00%	0.00%	0.00%	0.01%	0.02%	0.03%	0.02%	0.04%	**0.00%**
over 50	**0.00%**	0.00%	0.00%	0.00%	0.00%	0.01%	0.04%	0.06%	0.11%	0.12%	**0.00%**

Appendix 3: Sensitivity of the extent of temporal auto-correlation in the observation error

The extent of temporal auto-correlation in the observation error (ρ) undertakes the magnitude of time auto-correlation. This is an arbitrary number and is assigned as 0.5 in the simulation: 50% of biomass estimation error in last year affects the biomass estimation error in this year. Figure A3.1 shows the effect of change in ρ over time. The x –axis shows years and the y-axis shows average of observation biomass (3+) divided by (true) 3+ biomass ($\frac{\hat{B}_y}{B_y}$) over simulations (minimum biomass=0.5 B_0 and fraction=0.5) for each year steps. Since biomass estimation error is assumed as the normal distribution with mean=0 (C.V.=0.15) , the average of $\frac{\hat{B}_y}{B_y}$ over simulations must be around 1(error=0). In this simulation, however, the fixed initial error is given as 1 (η_1 =1 in Equation 4.1.3, and appears as $\frac{\hat{B}_y}{B_y}$ =2) to see the sensitivity of ρ in estimated biomass, and is induced over the estimation. Note that the affect of observation in one year exponentially decreased in subsequent years.

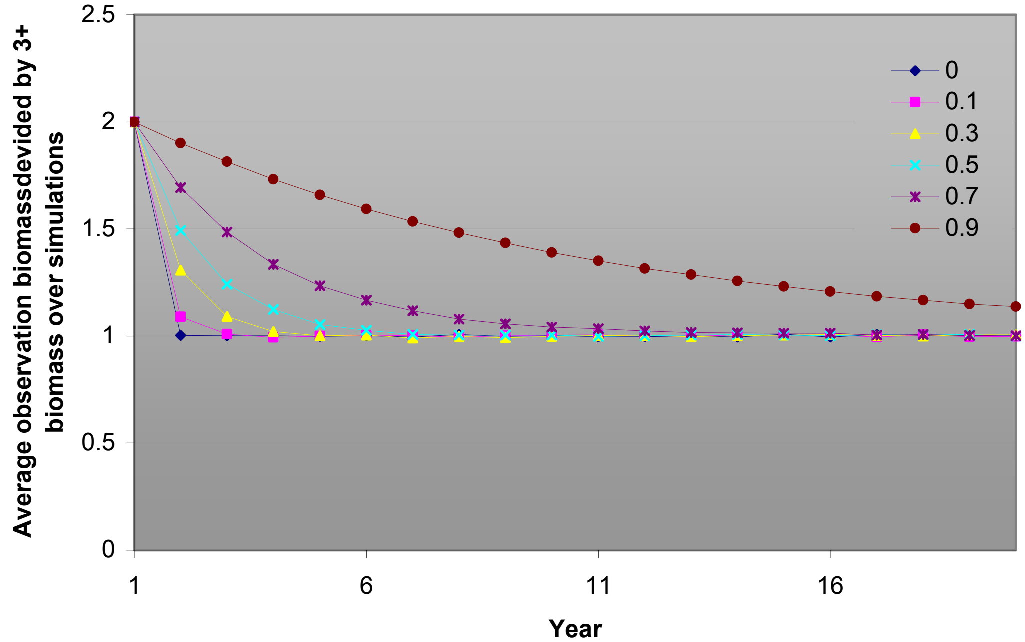

Figure A3.1. The sensitivity of extent of temporal auto-correlation in the observation error.

Figure A3.2 shows the affect of change in ρ for catch in the same simulation (η_1=1 in minimum biomass=0.5 B_0 and fraction=0.5). The x –axis shows years and the y-axis shows average total catch over simulations for each year. Although the affect of temporal auto-correlation in the observation error is dependant on the magnitude of error, which affects following years (in this case given as η_1=1), ρ=0.7 and 0.9 illustrate strong effects of over estimation in the second year.

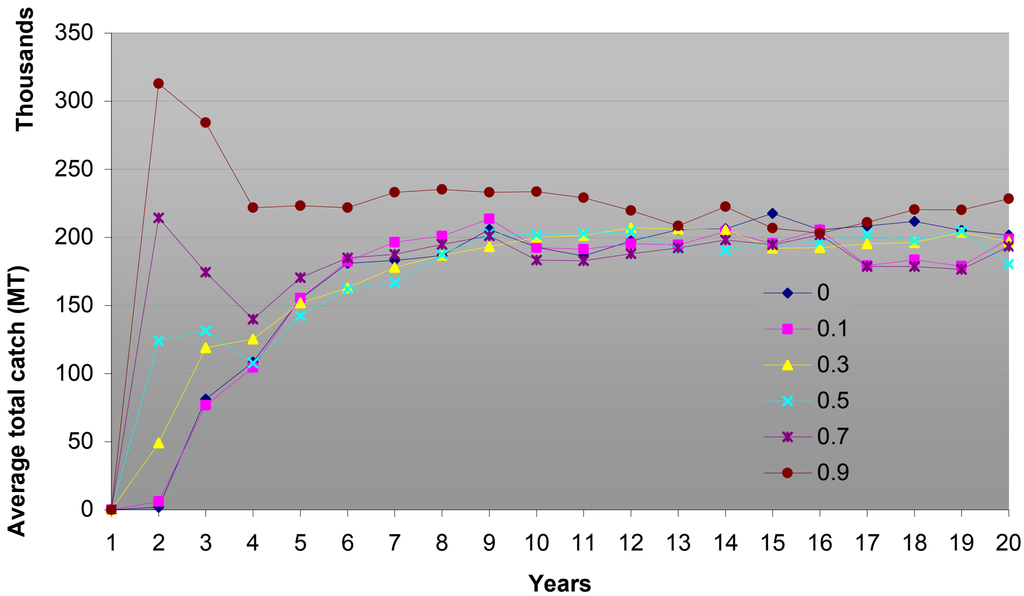

Fig. A3.2. Affect of change in ρ for catch in the same simulation (η_1=1 in minimum biomass=0.5 B_0 and fraction=0.5).